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ICE/HULL FRICTION COEFFICIENT STUDY

- MAIN REPORT -

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17. Abstract

This report documents a research project on ice/hull friction which a) reviews the different methods of hull surface roughness measurement, b) reviews the current methodology of hull surface representation and simulation at model scale, c) summarises the influence of each ice/hull interaction variable on friction coefficient, d) conducts a series of ice sample friction tests against carefully prepared reproductions of model surfaces, and e) conducts a series of level ice resistance model tests for three friction coefficients on the parallel midbody and bow of the M.V. ARCTIC.

The results of the work indicated that there were a number of factors which will influence the effective friction coefficient between the ice and the hull, and that the ice/hull friction is not Coloumb. The model tests, which were conducted with nominal friction coefficients 0.004, 0.060 and 0.400, demonstrated that friction has a significant effect on the resistance of the model. However, the augment of resistance associated with higher friction coefficients on the bow and midbody was not additive, i.e. the total increased resistance for a combined rough midbody and bow was less than the resistance obtained by adding together the resistance increase measured by testing the rough midbody and rough bow separately.

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17. Résumé

Ce rapport concerne une recherche sur le frottement des glaces contre les coques de navires. L'auteur y décrit: a) différentes méthodes de mesure de la rugosité des coques de navires, b) passe en revue les méthodes actuelles de représentation de l'état de surface des coques et de simulation de leur comportement tribologique à échelle réduite, c) décrit le lien entre le coefficient de frottement mesuré et chacune des variables d'interaction glaces/coque, d) rapporte les résultats d'une série d'essais de frottement d'éprouvettes de glace sur des éléments représentant fidèlement l'état de surface des coques modélisés et, e) commente une série d'essais des résistances à l'avancement dans une glace uniforme, la maquette du N.M. Arctic utilisée présentant trois coefficients de frottement différents dans la section médiane de la coque et sur la proue.

Les résultats des travaux révèlent qu'un certain nombre de facteurs influencent le coefficient de frottement réel entre la glace et la coque d'un navire et que ce frottement n'est pas conforme au schéma de Coloumb. Les essais sur maquette réalisés à coefficients de frottements nominaux de 0,004, 0,060 et 0,400 ont montré que ce facteur influait considérablement sur la résistance à l'avancement. Cependant, les résultats révèlent que l'effet de l'augmentation du coefficient de frottement sur la proue et dans la partie médiane de la coque n'était pas cumulatif, c'est-à-dire que l'augmentation globale de résistance due à la rugosité augmentée des deux segments de coque considérés est inférieure à celle obtenue en additionnant les augmentations de résistance attribuables à la proue et à la section médiane de la coque prises séparément.

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1. INTRODUCTION

From 1982 to 1984, Melville Shipping Ltd. (Melville) conducted an extensive model test programme associated with the bow redesign of the Arctic Class bulk carrier M.V. ARCTIC. The test programme involved two bows, the ship's original bow and a new bow designed by Melville. The ship was refitted with the new bow, known as the 'Melville' bow, in 1985/86, and tested, in ice, during the spring of 1986. The results of the full scale test programme highlighted correlation problems between the ship's predicted performance, based on the model tests, and the measured full scale performance. This correlation problem existed for both the original bow and the new Melville bow.

One possible explanation for this correlation problem was identified as the model scale representation of the hull surface and the ice/hull interaction, or friction coefficient.

The surface interaction between the hull of an icebreaking ship and the surrounding ice cover is a function of the type of ice, the presence of snow, the roughness and topography of the hull surface, the presence of lubrication, and the normal forces between the ice and the ship's hull. It is normal for this interaction to be quantified using a friction coefficient defined in some way by the normal and tangential forces present at the point of contact. The normal procedure for evaluating the friction coefficient at full scale is to drag ice samples over the ship's side or samples of hull steel over the ice. In both cases it is often assumed that coulomb friction (constant ratio of normal and tangential forces independent of force magnitude) is predominant and the ship's hull surface is categorised with the friction coefficient calculated from these tests. This non-dimensional coefficient is then used at model scale to represent the full scale hull surface. However, there are a number of disadvantages to these conventional procedures which are identified in this report and more recently the friction coefficient has been measured directly using instrumented plates on the bow and midbody of two icebreaking ships. The results of this analysis have shown that the friction coefficient at full scale is dependent on the normal force, the ship speed and the type of ice.

In view of the importance of the friction coefficient a research project has been completed to review the methods presently used to characterise the hull surface and to conduct a series of model tests to investigate this phenomenon in more detail. The work described in this report has been divided into two parts; a literature review of pertinent information, and a model test programme.

2. FRICTION COEFFICIENT REVIEW

2.1 General

The importance of the friction coefficient on the total resistance of an icebreaker has been recognised for several years. Kashteljan (1968) emphasised this importance and reported on some of the early experiments. In general, this early work represented the friction coefficient as coulomb, independent of contact forces. Coulomb friction may be defined by the relationship:

Tangential Force = (Constant) x Normal Force

The constant in this expression is defined as the coefficient of friction. More recent studies have indicated that the mechanism of the ice/hull interface is more complex and may be more accurately represented by:

Tangential Force = (Constant) x Normal Force + Offset

The constant in this expression is the friction coefficient and the offset is dependent on the surface conditions.

It is common to investigate the friction coefficient in three forms:

- breakaway,
- static, and
- dynamic.

Breakaway friction may be defined using the tangential force and normal force required to produce relative motion between two surfaces that have been in static contact for some period of time. In the case of ice and the ship's hull, this period of contact results in adhesion of the ice onto the hull.

Static friction may be defined using the tangential force and normal force required to produce relative motion between two surfaces that have been in static contact for a very short period of time.

Dynamic friction may be defined using the tangential force and normal force required to maintain relative motion between two surfaces that are in motion. In some cases the dynamic friction between ice and the hull is subdivided again into fast relative motion and slow relative motion due to the different interface mechanisms that are believed to occur in the two scenarios.

For the purpose of this report, only the dynamic friction coefficient is discussed in detail, although references are made to the breakaway and static friction coefficients where appropriate.

There are many factors that affect the numerical value attributed to the coefficient of friction between the ice and ship's hull. The key variables are:

- equipment used to measure the friction coefficient,
- surface variables including surface roughness and profile,
- ice variables including roughness, surface profile and mechanical properties,
- normal force, and
- speed,

The influence of each of these variables has been studied at model and full scale. In the general case the different variables will be reviewed based on the most common test, which is an ice sample dragged over the sample surface. Variations on this test procedure are discussed in each section as appropriate. The following sections review and discuss each variable and their perceived influence on the friction coefficient at model and full scale.

There are a number of methods currently used to define the 'roughness' of any given surface. Two identical forms are used in this report, the CLA, or Centre Line Average and RA, or Roughness Average. In both cases the value is defined by the average arithmetic roughness of a sample. This is obtained by defining a surface through the roughness profile that has an equal area of peaks above and troughs below. This is then used to calculate the average maximum peak and trough deviations, from this surface, which is defined as the roughness value.

2.2 Equipment Used to Measure the Friction Coefficient

Due to the nature of the hull interaction and the sensitivity of the interaction to the many ambient and mechanical variables, the procedure used to measure the friction coefficient will affect its absolute value. As a result, standard procedures are being developed both at model scale and full scale.

a) Full Scale

There are a number of methods used to measure the ice/hull friction coefficient at full scale. These may be summarised as;

- sledges dragged over the ice surface,
- ice samples dragged over the ship's hull,
- ice samples crushed against the ship's hull, and
- instrumentation integrated into the ship's structure to measure the tangential and normal forces on the hull whilst ice-breaking.

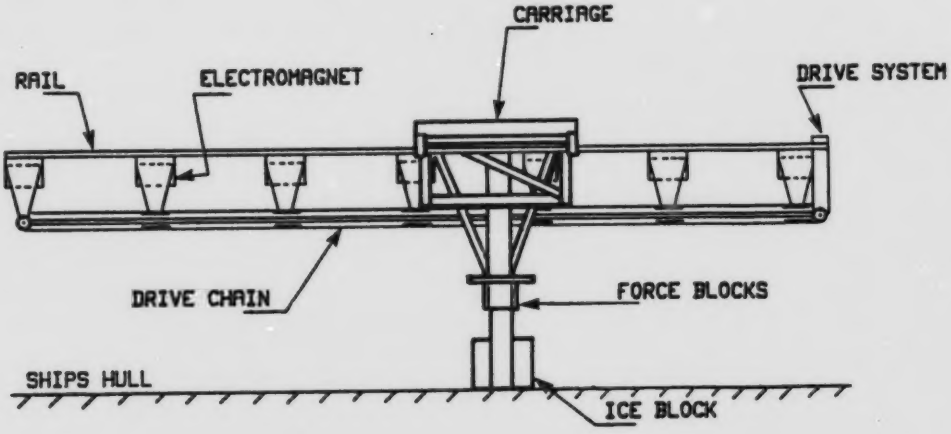
The most common of these methods is to drag samples, with or without any associated coating, across an ice surface. Enkvist (1972) conducted a series of tests using samples of different materials attached to the bottom of a sledge which was then dragged across the ice surface. The sledge measured 0.650 by 1.620 m and was loaded with weights to give a pressure range of between 1.30 and 20.00 kPa. It was pulled using a tractor over natural ice.

Similar tests were conducted by Calabrese (1976) using a sledge with two prepared surfaces. One side was fitted with two runners measuring 0.076 by 0.914 m long. The reverse side, with a similar surface finish, was a flat plate measuring 0.711 by 1.120 m. The sledge was tested on both sides to investigate the influence of surface area on the friction coefficient and loaded with weights to give a pressure range from 6.89 to 172.40 kPa. The experiments were conducted on artificial ice in a skating arena.

In an attempt to evaluate the friction coefficient between the ice and hull surface, experiments have been conducted using a carriage and rail system alongside the ship. Arctec Inc. (1982) conducted friction tests using this type of equipment during the USCGC POLAR STAR full scale tests in 1982. A schematic of the instrument is shown in Figure 2.1. The system consists of a rail assembly and carriage. Ice samples are held with an instrumented sample holder capable of measuring the normal and tangential forces between the ice and the hull. The carriage can be adjusted to ensure that the ice sample is normal to the hull surface. The test is conducted by using the carriage to drag the ice sample along the ship's side. The equipment used during the 1982 tests of the POLAR STAR was capable of 0.91 m/sec and normal forces of 1.78 kN. The effect of the different sample sizes could not be studied from the limited information in the report.

FIGURE 2.1

SCHEMATIC OF TRIAL AND CARRIAGE FRICTION MEASURING DEVICE

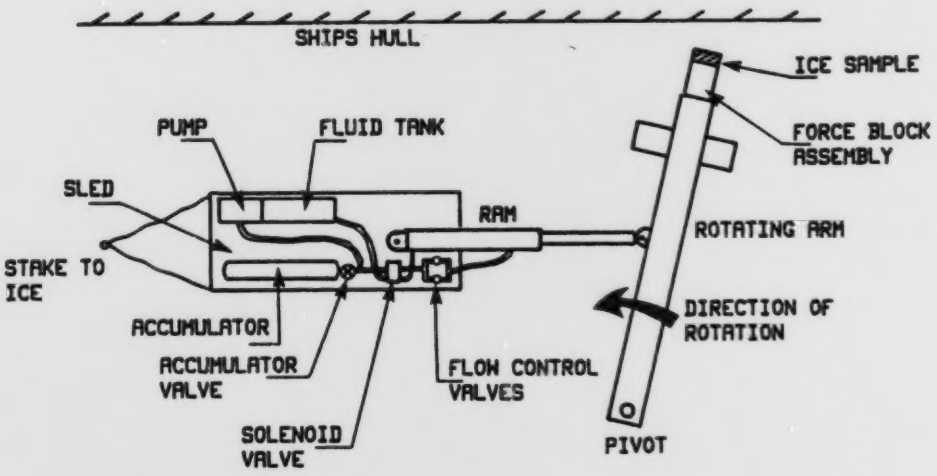


FROM ARCTEC 1982

The rail and carriage system described above records the friction coefficient of an ice sample dragged along the ship's hull. However, the hull ice interaction during icebreaking has been observed to include both crushing and sliding components. Responding to this different ice/hull interaction, a swinging arm method was developed to include both sliding and crushing mechanisms. Figure 2.2 shows a diagram of the equipment.

FIGURE 2.2

SCHEMATIC OF SWINGING ARM FRICTION MEASURING DEVICE



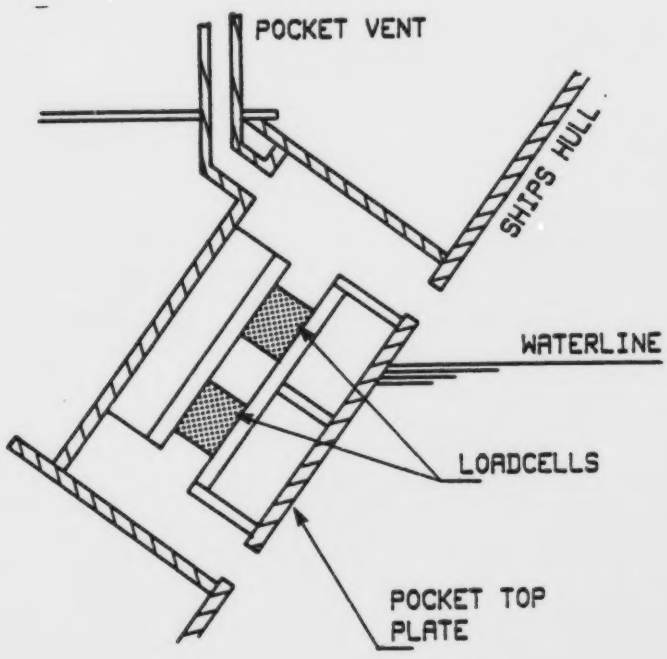
FROM ARCTEC 1982

The ice sample is held at the end of an aluminium arm pivoted around a pipe that is driven into the ice. The arm is rotated with a hydraulic ram in such a manner as to bring the ice sample against the ship's side and, as the arm is rotated, the ice is crushed against the hull surface. The equipment used during the 1982 tests of the POLAR STAR (Arctec Inc. 1982) was capable of speeds up to 4.3 m/sec and normal forces of 22.24 kN. Unfortunately, from the limited information in the report, it is not possible to examine the effect of sample size or pressure. The rotating arm equipment used during these 1982 tests resulted in highly scattered data points which were inconsistent with the rail and carriage experiments conducted at the same time. The reasons for this inconsistency is suggested to be either inaccuracies in the measuring and recording system or inconsistent performance of the rotating arm device. Based on these tests, although it may offer a more representative ice/hull interaction, the reliability of this type of equipment to produce consistent data would appear to be suspect.

More recently the friction coefficient has been measured directly from the ship's hull during icebreaking operations. There are two ships that have been instrumented with load cells to record normal and transverse forces exerted on the hull. Hoffman (1986) describes the instrumentation on the German polar research vessel POLARSTERN, and Enkvist (1986) describes similar equipment on the icebreaking tug PROTECTOR. A schematic of typical instrumentation is shown in Figure 2.3.

FIGURE 2.3

SCHEMATIC OF THE HULL INSTRUMENTATION ON BOARD THE POLARSTERN



FROM HOFFMAN 1986

Two load cells were fitted to the POLARSTERN, one toward the front of the bow and one at the shoulder. Both load cells were about 0.8 by 1.4 m and located at the icebreaking waterline. The cells were designed to measure loads up to 4,000 N.

On the PROTECTOR the load cells were smaller. One 0.260 m in diameter was fitted in the bow and a second, 1.00 m in diameter, on the bottom.

Experiments were conducted on both of these vessels and reported as successfully recording a range of friction coefficient as a function of ship speed and normal force. Clearly this is the most direct procedure for measuring the coefficient of friction although, once the load cell location is selected and installed, the sampling area is fixed. The installation and reliability of the equipment is also difficult to guarantee since the location of the load cells will often be associated with high, normal and tangential forces. This problem was highlighted by the damage sustained to one of the load cells fitted to the POLARSTERN during the 1985 tests.

b) Model Scale

There are two objectives to measuring the surface condition of the model. The first is to establish control of the model surface characteristics so that tests, using different models, may be repeated using the same surface characteristics. The second is to define a relationship between the full scale hull surface and the model hull surface.

It has been common practice to prepare the hull surface of models using a spray paint and then sanding or buffing the surface to achieve the target roughness. This procedure is labour-intensive and not very consistent. As a result, model tanks are developing paint additives that can be used with a spray gun to control surface roughness during painting. Using this method, no additional surface preparation is required and control of the surface uniformity is better. This procedure is discussed in more detail in Section 3.

There are three procedures that have been adopted to measure the model surface characteristics:

- An ice sample on the model surface.
- An ice sample on a panel which has been treated with the same surface preparation as the model.
- Roughness gauges and correlation to an equivalent friction coefficient.

There are advantages and disadvantages to each of these methods.

Testing the model surface with an ice sample is restrictive since only the flat parts of the model can be tested with any degree of control. Providing the model has a suitable flat surface, a consistent paint coating has been applied to both the flat and curved parts of the model, and the test equipment is designed to be accurate over a range of different model types and sizes, this is the best method to adopt. Unfortunately, many icebreaker models do not have suitable areas of flat hull, and equipment suitable for measuring the friction coefficient on a range of different model sizes has not yet been designed.

Testing a sample panel provides the opportunity to establish the ideal test procedure since the panel can be made to a standard size to fit into a test rig. The problem with using a panel is associated with the need to duplicate the paint surface of the model onto the panel. With careful control of the painting procedure this is possible but should be checked at regular intervals to ensure consistency.

Very few model tests, if any, have been conducted based on the roughness of the hull surface. Experiments have been conducted to establish the relationship between the surface roughness and friction coefficient but these have not been used to define the friction coefficient of the hull.

The standard model scale procedure for measuring the friction coefficient consists of pulling weighted ice samples across the subject surface. International standards were adopted by the International Towing Tank Conference (ITTC 1981), which were defined in association with a model test series of the R-Class icebreaker and panels supplied by the National Research Council of Canada. The panels were coated with the same surface as the model. Since this conference, more recent standards have been proposed by ITTC based on a sample of ice dragged across a board of the same material and surface finish as the model. These new recommendations are:

Velocity:	> 0.10 m/sec
Surface Pressure:	0, 1, 2 and 4 kPa
Ice Surface:	Top surface
Temperature:	Test air temperature -0.5^{o}C
Condition:	0.003 m water layer on sample surface
Sample Size:	0.01 to 0.02 m^2

Notwithstanding the standard friction tests, there are a number of different test procedures used at the different ice tanks.

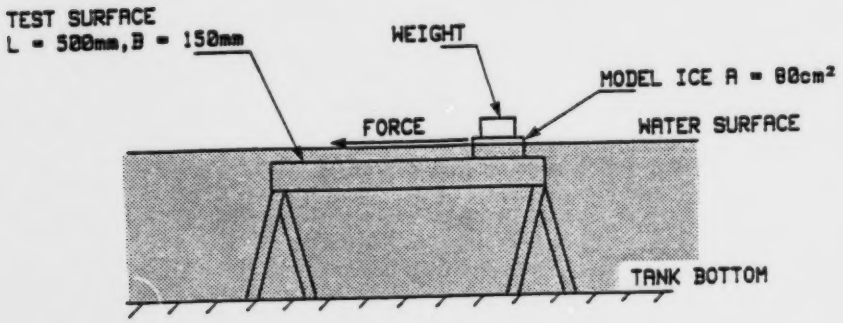
The method adopted by Arctec Canada Limited (1982) during model tests in 1982, was to pre-cool and wet the model surface and then drag a block of ice over the model by hand using a simple spring load cell. The speed control is limited and relies on the laboratory technician to duplicate speeds in successive tests. The target speed of the sample was reported to be 0.1 m/sec

During 1984, the Wartsila ice tank (1984) recorded the friction coefficient using a sample surface supported under water. To date, there is no published correlation between these tests and those using ice samples above water. A schematic of the Wartsila equipment is shown in Figure 2.4.

Calabrese (1974) used a drill press that rotated the test material against a sample of ice. The test material was in the form of a ring 0.05 m outside diameter and 0.032 m inside diameter. The tangential forces were recorded by instrumenting the ice sample holder which was free to rotate on bearings. A schematic of the equipment is shown in Figure 2.5.

FIGURE 2.4

SCHEMATIC OF FRICTION JIG USED BY WARTSILA
FOR UNDERWATER FRICTION MEASUREMENT



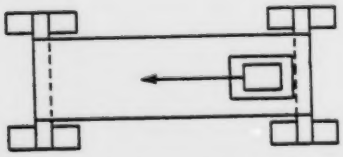
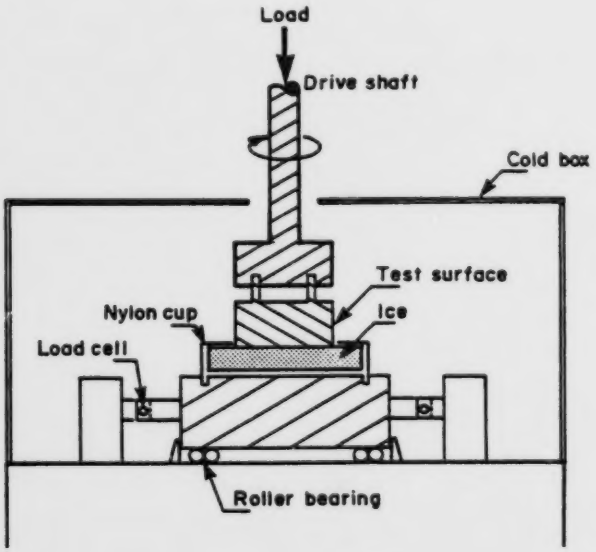


FIGURE 2.5

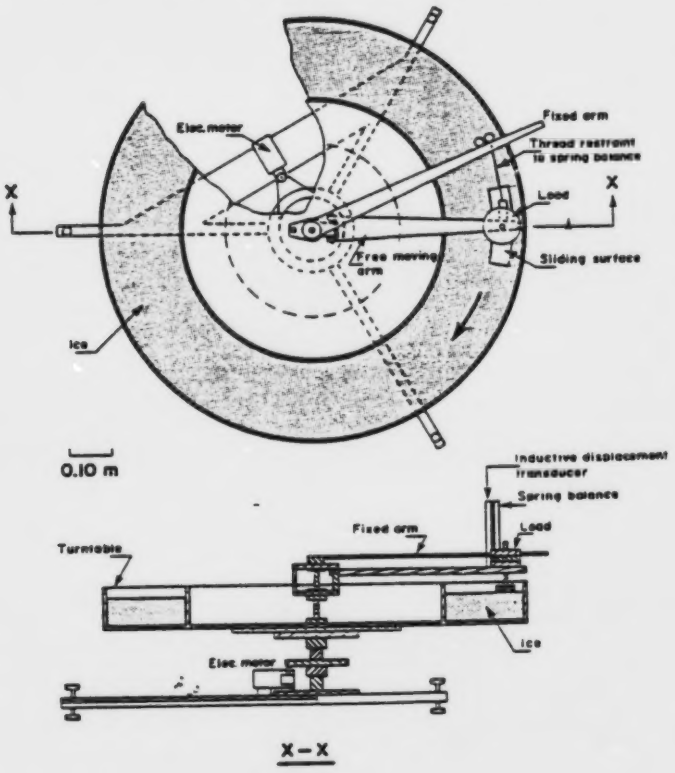
SCHEMATIC OF FRICTION JIG USED BY CALABRESE
FOR FRICTION MEASUREMENTS



Oksanen (1980) used equipment that rotated the sample on a radial arm over a circular bed of ice. A schematic of the equipment is shown in Figure 2.6. The circular bed of ice is about 0.8 m diameter. The sliding surface is attached to the rotating arm, which is driven by a motor. The sliding surface could be loaded, and the tangential force recorded using a cord and spring balance. The test specimen was prepared in the form of a ring section, 225 mm long and 51 mm across, with an 800 mm diameter curvature. Normal loads ranged from 10 to 50 N or 0.87 to 4.357 kPa, with a speed range of 0.5 to 3 m/sec.

FIGURE 2.6

SCHEMATIC OF APPARATUS USED BY OKSANEN (1980) FOR MEASURING FRICTION COEFFICIENT



FROM OKSANEN 1988

IMD has recently constructed apparatus that slides the prepared surface panel beneath a stationary ice sample. The ice sample is fixed to a sample holder using fresh water ice and then balanced with a counter weight. As a result the ice self-weight is not included in the normal force generated by placing weights on the sample holder. A motor and screw drive is used to move the panel at a constant speed below the ice sample. The tangential force on the ice resisting the panel movement is measured using load cells located on the ice sample holder. This equipment is considered to be the best arrangement since it offers the capability of testing a range of sample sizes and speeds with varying loads. This test apparatus is described in detail in Section 3.

2.3 Material Surface Variables

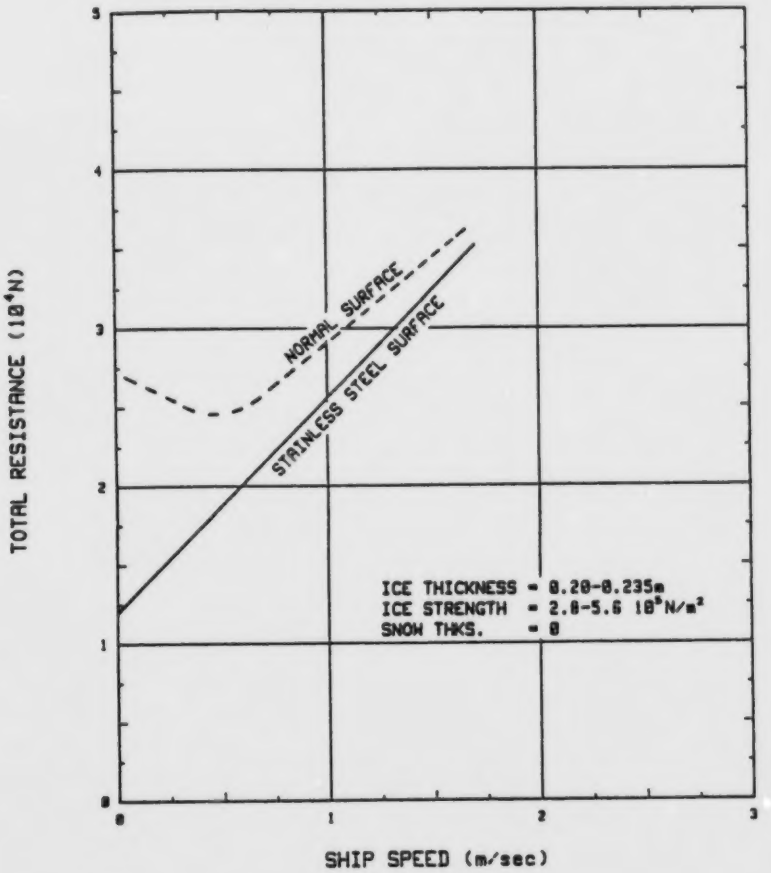
a) Full scale

The effect of roughness on the friction coefficient at full scale has been studied by a number of authors. Makinen (1975) describes three sets of experiments on the icebreaking tug JELPPARI and two similar Finnish Coast Guard cutters, the SILMA and the VALPAS. In addition Makinen also describes hull surface tests on the MURTAJA and JERMAK.

The performance tests on the JELPPARI were conducted before and after the installation of a stainless steel belt around the tug's bow at the waterline. Figure 2.7 shows the effect on level icebreaking performance of the tug with and without the stainless steel plates. The results from these tests verified the influence of hull surface roughness of resistance. In addition, it can be seen from the tests that the effect of friction on resistance is dependent on speed. At low speeds the influence of the rougher hull is considerably stronger than at higher speeds where the effects of friction tend to be lower.

FIGURE 2.7

AFFECT OF HULL SURFACE ROUGHNESS ON THE LEVEL ICE PERFORMANCE OF THE TUG JELPPARI



FROM MAKINEN 1975

Samples of the hull plate were also cut from the tug and tested independently. Samples of ice were pulled over the hull samples with different loads and using different ice sample types. The results of these tests are shown in Figure 2.8 and it can be seen from this figure that the stainless steel surface gives consistently lower friction coefficients. The ice surface also has a significant effect on the friction coefficient and this is discussed in more detail in a following section.

The second set of tests reported by Makinen were conducted over four winters on two similar Finnish Coast Guard cutters, the SILMA and VALPAS. The first set of tests with both ships were conducted in the winter of 1972. Unfortunately, no discrete friction measurement were recorded before or after the tests. The SILMA was nine years old and the VALPAS, with an noticeably smoother hull surface, was two years old. The results of the tests are shown in Figure 2.9.

In 1973, the VALPAS was painted with a conventional hull paint and the SILMA was sandblasted and coated with a solvent-free epoxy coating, and the two ships pre-tested. The results of these tests are also presented in Figure 2.9 together with the results of the earlier tests. It can be seen from this figure that the effect of resurfacing the hull of the SILMA was a significant reduction in resistance. The resistance of the VALPAS was reported to have increased due to the aging of the hull, since the conventional paint did not reduce the hull resistance. This result clearly highlights the importance of surface morphology.

In 1973 several hull coatings were tested on the MURTAJA and JERMAK to investigate the types that should be used on icebreakers. The tests were conducted using seven different hull coatings. A list of the different coatings is presented in Table 2.1

The results of these tests were summarised as:

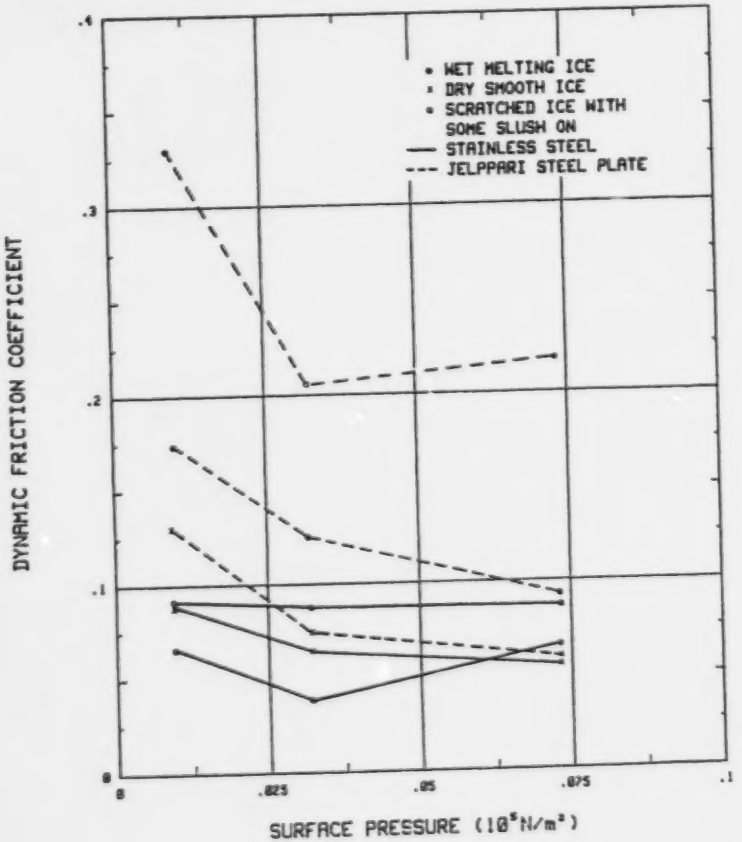
- the solvent free epoxy was the only coating not to be damaged,
- the failure of the coal tar epoxies was considered to be due to their embrittlement at low temperatures,
- the area of heaviest ice abrasion is a narrow zone (two to three meters) at the waterline.

These conclusions were supported by Calabrese (1974; 1976; 1978), who conducted a series of laboratory and full scale tests to examine a range of surface coatings for icebreakers.

The work was undertaken in three phases, which included laboratory work and full scale tests on a number of US Coast Guard icebreakers. The results of the work identified two of the most popular paint coatings used on icebreaking ships, Zebron, a non-solvent polyurethane, and Inerta 160, a non-solvent epoxy, as the most promising coatings for icebreaking hulls. Full scale tests were conducted on two icebreakers, the USCG cutter ARUNDEL and the USCG cutter RARITAN. The ARUNDEL was coated with a bituminous epoxy and the RARITAN with Zebron. Figure 2.10 compares the results from the level ice tests and demonstrates an eight to 15 percent improvement of the Zebron coating over the bituminous epoxy.

FIGURE 2.8

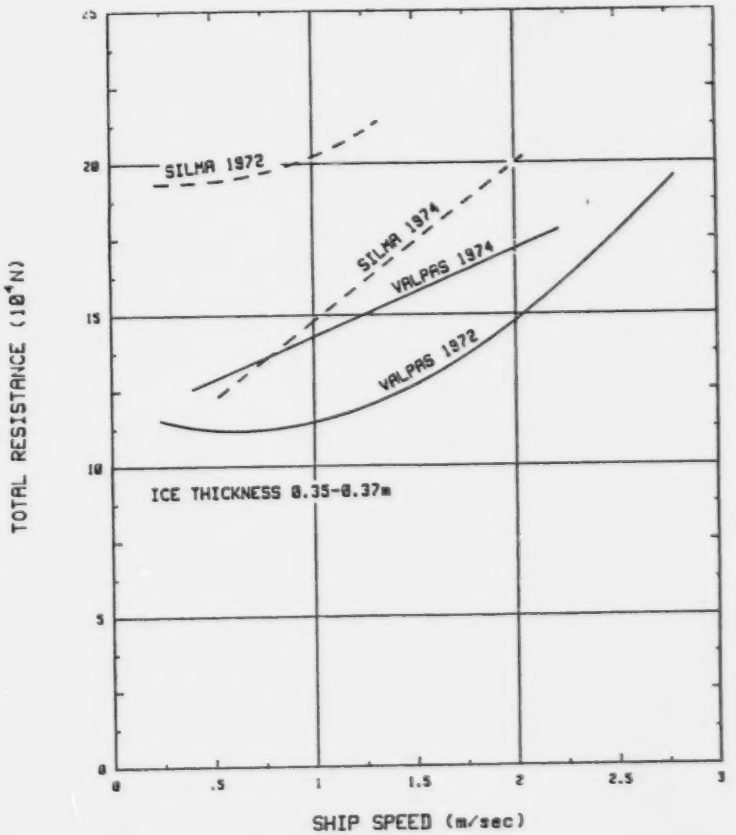
FRICTION MEASUREMENTS RECORED FROM THE TWO HULL SURFACES OF THE TUG JELPPARI



FROM MAKINEN 1975

FIGURE 2.9

TEST RESULTS WITH THE SILMA AND VALPAS WITH DIFFERENT HULL SURFACES



FROM MAKINEN 1975

TABLE 2.1

HULL COATINGS TESTED ON THE ICEBREAKERS MURTAJA AND JERMAK IN 1973/74

COATING SYSTEM	PAINT THICKNESS (um)	COMMENTS
1 x Zinc Silicate 2 x Coal Tar Epoxy	60 220	Tested on the MURTAJA and JERMAK, coating totally worn away.
2 x Coal Tar Epoxy	220	Tested on the MURTAJA and JERMAK, coating totally worn away.
1 x Epoxy Smoothing Compound 2 x Coal Tar Epoxy	> 1,000 220	Tested on the MURTAJA and JERMAK, coal tar epoxy worn away, epoxy undamaged.
1 x Solvent Free Coal Tar Epoxy	400	Tested on the MURTAJA and JERMAK, 50 percent of coating split off.
1 x Epoxy Smoothing Compound 1 x Solvent Free Epoxy	> 1,000 500	Tested on the MURTAJA and JERMAK, no damage. Surface glossy, showing original spraying pattern.
1 x Solvent Free Epoxy	500	Tested on the MURTAJA and JERMAK, no damage. Surface glossy, showing original spraying pattern.
1 x Zinc Silicate 2 x Epoxy	60	Tested on the MURTAJA, 90 percent worn away.
1 x Epoxy Primer 2 x Polyurethane	70 240	Tested on the MURTAJA, totally worn away.

The figure shows that the friction effects tend to increase with speed. This is an opposite speed dependency to the results published by Makinen and discussed above. The ice conditions were clearly different for both sets of tests but the opposite trends do highlight an anomaly in the two sets of results. Unfortunately, the Inerta 160 was not tested.

Hull surface roughness and friction coefficient were measured during the tests of the CCG RADISSON in 1978 and 1979 (Arctec 1979). The first set of tests were conducted in August 1978 in Arctic summer ice, characterised as being weak, thick, melting first year ice. The tests in February 1979 were in the Saguenay and St. Lawrence Rivers and the ice was characterised as being strong, fresh and saline ice, up to about 0.8 m thick. The tests were conducted on painted and bare hull surfaces. The tests demonstrated that two surfaces with a similar roughness (painted hull and bare steel, 7.82 and 7.3 μm Centre Line Average (CLA) respectively) appeared to have significantly different friction coefficient values (0.09 versus 0.19). This is attributed to the weaker ice conditions during the 1978 tests, which were associated with the bare steel and high friction coefficient. However, it is considered possible that the morphology of the two surfaces may also have contributed to the difference.

b) Model Scale

Many tests have been conducted by experimenters on different surface roughnesses to obtain a correlation between roughness, the CLA value, and the friction coefficient. The results of these tests usually confirm that, as the materials get rougher, the material/ice friction coefficient tends to increase. However, the surface morphology has also been found to be very important and, in some cases, surfaces with the same CLA value have significantly different friction coefficients.

Calabrese (1974; 1976; 1978) conducted many laboratory tests with a range of different surfaces and materials. The tests were conducted with the rotating drill press described in Section 2.2. The effect of roughness was examined at a range of temperatures and under different loading conditions. Figure 2.11 shows the effect of surface roughness on the friction coefficient at low temperature, -22°C, and under a pressure of 41 kg (90 lbs).

It can be seen from this figure that the kinetic friction coefficient only increases from about 0.08 to 0.12, for a roughness increase of 1.0 to 6.1 μm CLA, whilst the static and breakaway friction values increase significantly over the same roughness range. Above a critical temperature, the effect of roughness on the friction coefficient changes significantly. In the case of ice against steel this tends to occur at about -7°C.

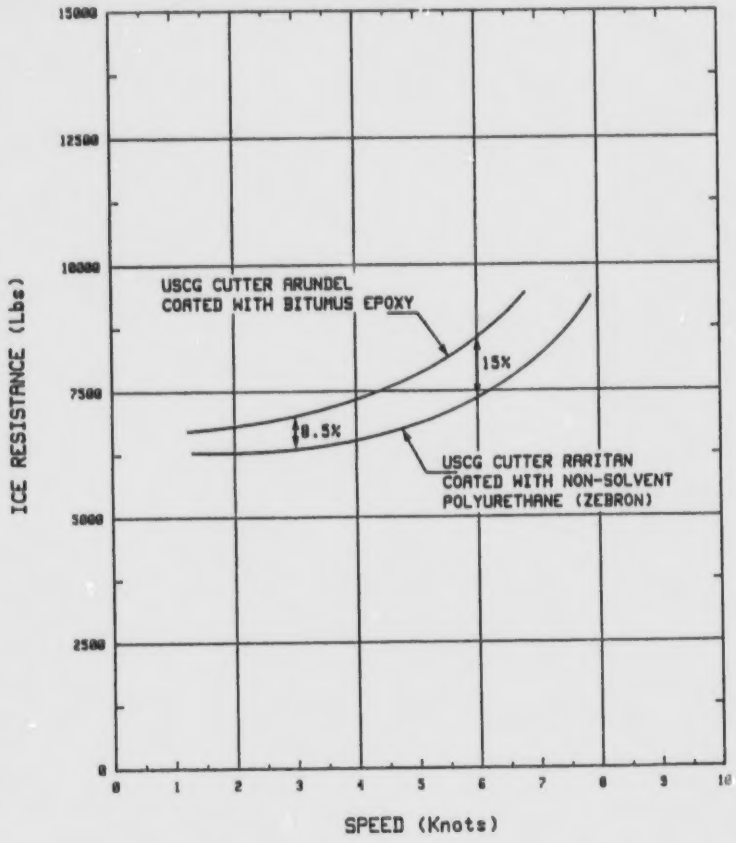
The effect of roughness on the friction coefficient shown in Figure 2.11 represent low temperatures and relatively high pressures. At higher temperatures and lower pressures there appears to be a sharp increase in the kinetic friction coefficient between about 0.5 to 1.0 μm CLA. Figure 2.12 shows this rapid increase from experiments conducted by Forland (1985). This phenomenon is thought to be due to the mechanical properties of the ice and is discussed in more detail in another section.

In addition to roughness, the morphology and thermal properties of the interfacing surfaces also affects the friction coefficient (Forland 1985; Oskanen 1980). Three different surfaces were tested with similar roughnesses (Forland 1985); stainless steel (0.33 μm CLA), aluminum (0.30 μm CLA) and Inerta 160 (1.60 μm CLA). Although the Inerta 160 had the roughest surface, it exhibited the lowest friction coefficient. This is believed to be due to both the different type of surface, wetting or non wetting, and the lower thermal conductivity of the Inerta 160 compared to steel and aluminum. This will tend to increase the temperature at the surface interface and increase lubrication.

Sample tests conducted in association with the POLARSTERN trials in 1984 (Tatinclaux 1985) examined Inerta coated surfaces and bare steel plate under wet and dry conditions. The friction coefficient was found to vary significantly as a function of the material surface. Surfaces that exhibited a low surface tension characteristic, a wetted surface such as the bare steel, exhibited a higher friction coefficient than a water repellent surface, such as the Inerta. In addition, adding water to the Inerta coated surface did not significantly reduce the friction coefficient while wetting the bare steel surface significantly increased the friction coefficient. Figure 2.13 shows the effect of roughness and surface condition on the friction coefficient.

FIGURE 2.10

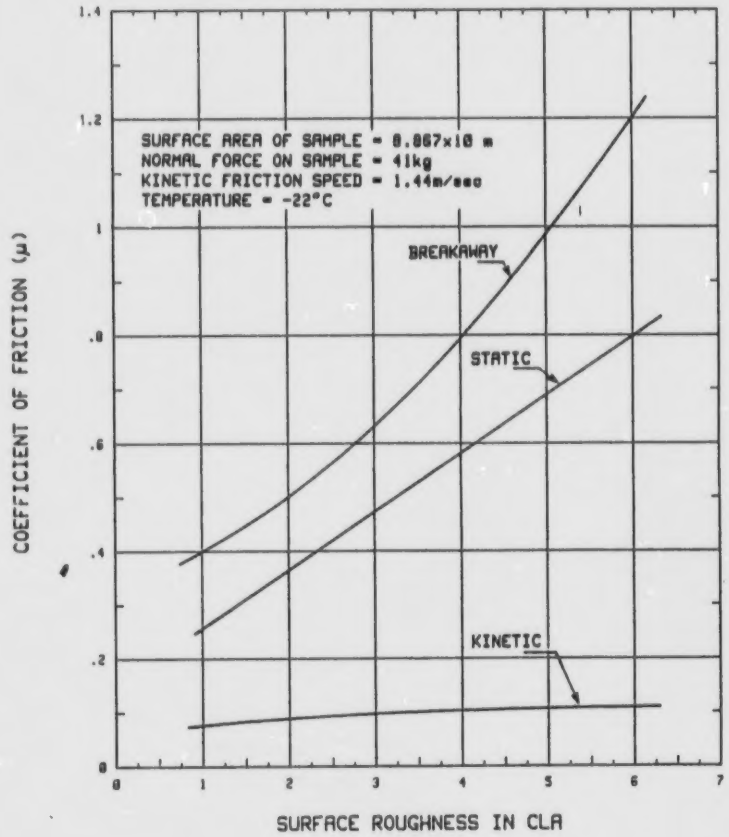
FULL SCALE TEST RESULTS ON TWO HULL COATINGS
ON THE USCG ARUNDEL AND USCG RARITAN



FROM CALABRESE 1978

FIGURE 2.11

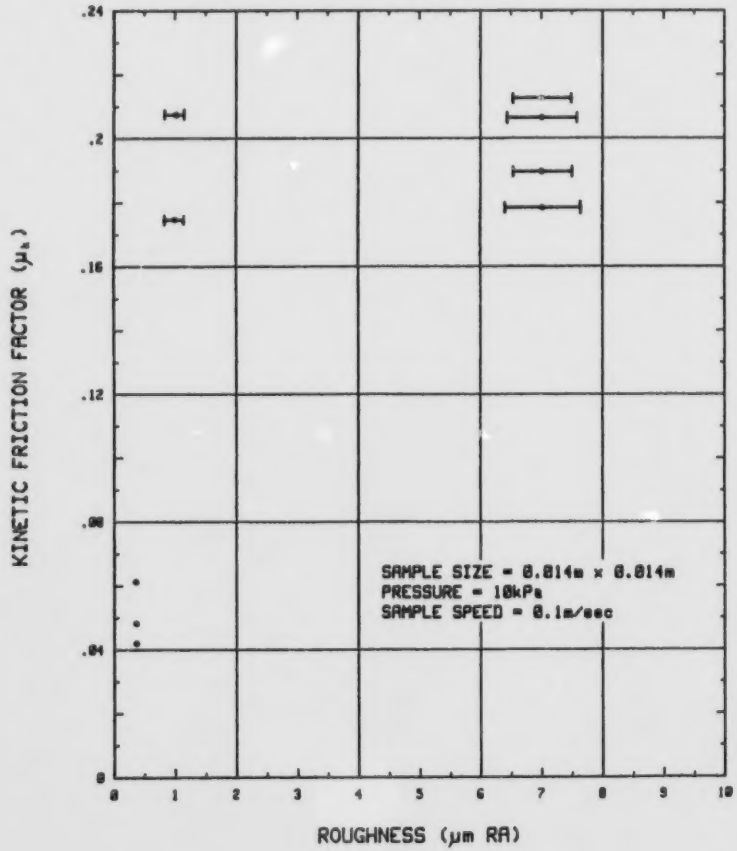
EFFECT OF SURFACE ROUGHNESS ON
FRICTION COEFFICIENT AT LOW TEMPERATURES



FROM CALABRESE 1978

FIGURE 2.12

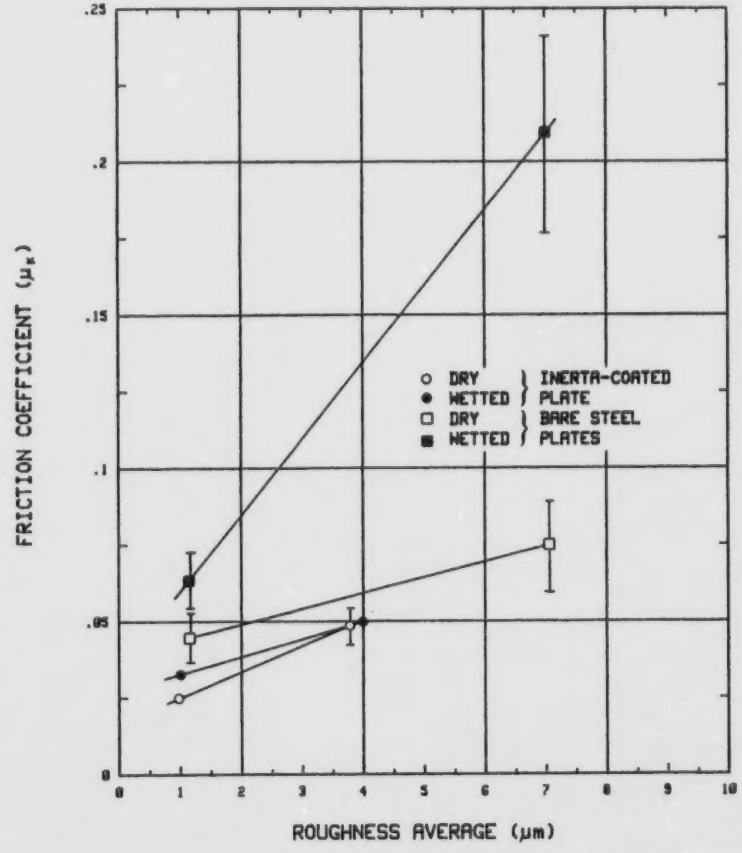
EFFECT OF ROUGHNESS
ON FRICTION COEFFICIENT AT 1.5°C



FROM FORLAND 1985

FIGURE 2.13

EFFECT OF ROUGHNESS AND SURFACE CONDITIONS
ON THE FRICTION COEFFICIENT



FROM TATINCLAUX 1985

2.4 Ice Variables

The mechanical and physical characteristics of the ice will effect its friction coefficient with other materials. Unfortunately the ice characteristics at full scale are rarely defined with any accuracy and usually only a general ice description is given. At model scale, the ice can be defined in more detail and specific trends identified.

a) Full Scale

Several tests have been conducted that examine the effect of ice properties on the friction coefficient. Enkvist (1972) conducted a series of sample tests with a 0.65 m by 1.62 m sledge loaded with weights, to give a range of pressure from 1.3 to 20 kPa. The ice was 0.9 percent saline, partly clean, partly covered with light snow, and partly covered with wet snow. The air temperature was -5°C. Results from the tests with a surface pressure of 10 kPa and a speed of 0.5 m/sec are shown in Table 2.2

TABLE 2.2

EFFECT OF ICE SURFACE ON FRICTION COEFFICIENT

MATERIAL	ICE	SNOW	WET SNOW
Stainless steel, smooth	0.025	0.099	0.066
Aluminium, smooth	0.033	0.089	0.069
Smooth painted steel	0.041	0.129	0.101
Sandblasted steel	0.045	0.189	0.036
Rough scrap steel	0.109	0.307	0.141
Static friction, 20 kPa Sandblasted steel	0.340	0.520	0.320

It can be seen from this table that the effect of ice surface condition is significant. In all cases the snow covered ice yields the highest friction coefficient and, in most cases, the bare ice yields the lowest. The advantages of a bow water wash system can be seen by comparing the wet snow and the dry snow friction coefficients. In every case, and particularly with the bare steel, there is a significant reduction in friction coefficient for wet snow compared with dry snow.

A similar increase in friction coefficient for snow covered ice is reported by German (1975). During tests of the CCGC WOLFE, a sledge was used to measure the surface friction coefficient. Two ice surfaces were tested; hard crusty snow, and freshly fallen snow. The friction coefficient for the hard crusty snow and the freshly fallen snow were about the same for high loads, but for lower loads the friction coefficient was from 50 to 100 percent higher for the freshly fallen snow than the hard crusty snow.

Unfortunately, very little information is available from the POLARSTERN full scale trials (Hoffman 1986) that give any valuable information on the effect of different ice surfaces on the friction coefficient. During the PROTECTOR trials (Enkvist 1986) the ship was run through snow covered, snow cleared and wet ice conditions and the friction coefficient measured from the load cells did not show any significant variation between any of these conditions.

b) Model Scale

The ice variables that have been studied at model scale to investigate their effect on the friction coefficient are:

- sample configuration,
- sample size,
- crystal orientation,
- surface morphology and
- mechanical properties.

The sample configuration has been shown to influence the measured friction coefficient at model scale (Forland 1985). Tests of an ice sample on a subject material resulted in significantly different friction values and trends than a sample of material on the ice. A possible explanation for this difference relates to the ice sample interface. In the case of ice on a material sample, the water at the surface interface will be replenished by drainage from the ice sample and ice melting due to the frictional heat. In the case of the material sliding on the ice, any surface fluid will tend to drain down through the ice and only limited time is allowed for ice melting as the material sample slides over the ice. To ensure equitable comparisons between test programmes, experiments are usually conducted with samples of ice moving relative to the test surface.

The effect of sample size was investigated by Forland (1985) using samples of ice sliding over a stainless steel sheet with a roughness of 0.36 μm CLA. The sliding velocity was 10 cm/sec with a normal pressure of 10 kPa. A range of sample sizes were tested from 16 to 400 cm^2, and there was no significant variation in friction coefficient. This result was confirmed by Calabrese (1976) for a series of small test samples (8.4 to 12.9 cm^2). During larger sample tests, using the weighted sledge in the ice arena, the larger surface (0.139 to 0.8 m^2) tended to exhibit higher friction coefficients although the tests with the larger surface were irregular and characterised by a "stick and slip" action rather than a smooth slide.

Varying the orientation of the ice sample with the test surface, i.e. ice crystals parallel or perpendicular, have not been shown to produce different friction coefficients (Forland 1985; Tatinclaux 1985).

The effects of surface morphology were investigated by Tatinclaux (1985). Figure 2.13 presents the results from the tests that compared a bare hull steel plate with an Inerta coated plate.

The results of the tests showed that the Inerta coated steel plate has a lower friction coefficient for similar roughness values than the bare

hull steel plate. It can also be seen from Figure 2.13 that water on the Inerta coated plate does not have a significant effect on the friction coefficient, whilst the effect of water on the bare hull steel plate is to significantly increase the friction coefficient. These results demonstrate that the magnitude and the morphology of a surface roughness, together with its surface tension characteristics when wet, greatly affect its friction coefficient with ice.

The influence of the mechanical properties of the model ice on the friction coefficient has been examined by Forland (1985), who conducted a series of tests using ice samples of different hardness.

For the case of an ice sample dragged over a stainless steel sheet (roughness 0.36 μm CLA at 10 cm/sec), the harder ice resulted in lower friction coefficients. This is attributed to the increased contact area that will exist between a soft ice sample and a hard sample for an equivalent pressure, and also to the increased water layer between the soft ice sample and material. Three ice hardnesses were tested; 375, 500 and 1,525 kPa. These values correspond to approximately 40, 46 and 85 kPa flexural strength. Figure 2.14 shows the three hardness values tested as a function of friction coefficient and pressure. The softer sample has the highest friction coefficient and is more sensitive to the normal pressure which will act to crush the ice and steel surface together. When the material sample was dragged across ice, the influence of hardness on the friction coefficient was negligible and emphasised the importance of the frictional heat generated in the ice sample causing ice melting at the surface interface.

The surface condition of the sample ice was examined by ten repeated tests of the same ice sample on Inerta (roughness 0.90 μm CLA) and roughened Inerta (roughness 3.80 μm CLA) surfaces (Tatinclaux 1985). The tests included ice samples oriented with crystals perpendicular and parallel with the test surface. In all cases the calculated friction coefficient did not significantly change from the first test to the last.

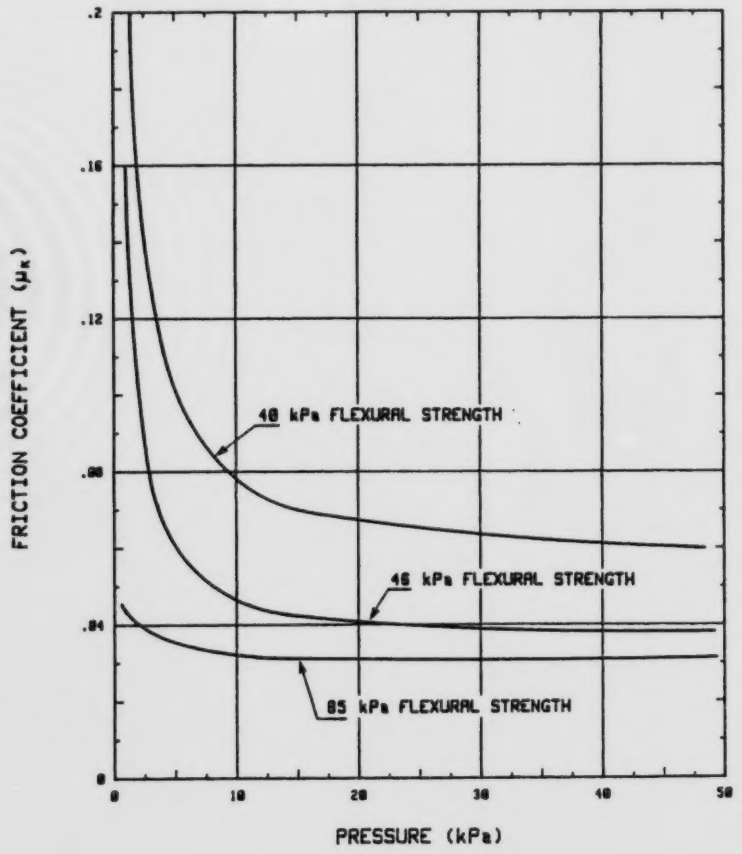
2.5 Normal Force

a) Full Scale

The full scale tests examining the effects of normal force range from sledge tests to instrumented panels on icebreaking ships. Enkvist's sledge tests (1972) included an analysis of normal load and tested a loaded sledge measuring 0.65 by 1.62 m over a pressure range of 1.3 to 20 kPa. The results of these tests indicated that the friction coefficient decreased with normal force to about 15 kPa and then remained constant. This relationship is shown in Figure 2.15 and this may be compared with tests by Ryvlin (1973), who reported tests completed with a sledge on wet ice and dry ice. The experiments were conducted over a pressure range of 9.8 to 22.5 kPa, in which no variation in friction coefficient was identified. This is considered to support the Enkvist results, although it is unfortunate that Ryvlin did not test in a slightly lower pressure range.

FIGURE 2.14

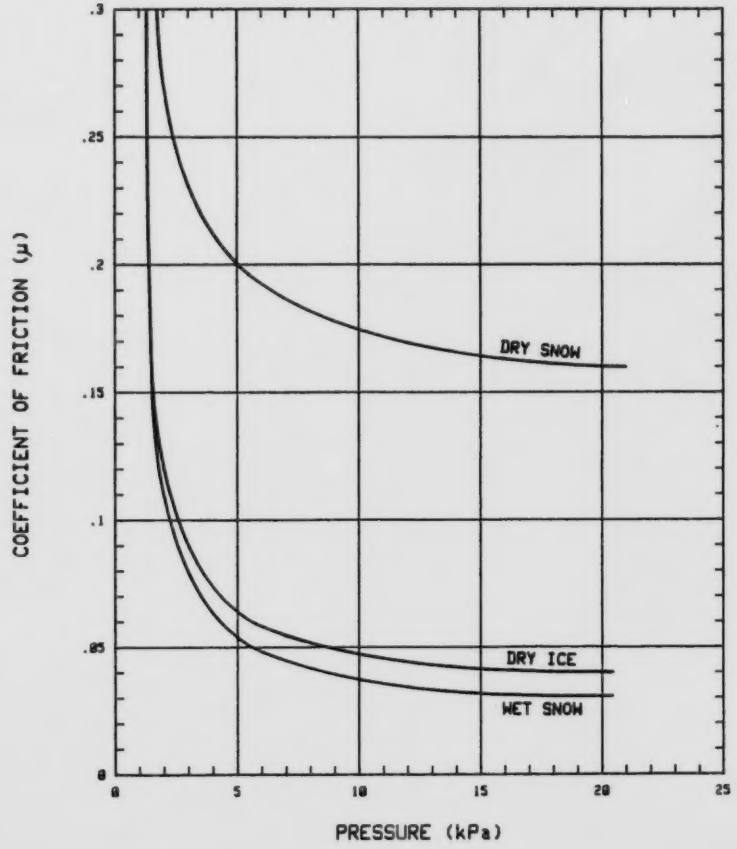
VARIATION OF FRICTION COEFFICIENT AS A FUNCTION OF NORMAL PRESSURE AND ICE HARDNESS



FROM FORLAND 1985

FIGURE 2.15

EFFECT OF PRESSURE ON FRICTION COEFFICIENT



FROM ENKVIST 1972

Instrumented panels to investigate the friction coefficient at full scale have been fitted to two icebreakers, the POLARSTERN (Hoffman 1986) and the PROTECTOR (Enkvist 1986). The POLARSTERN was fitted with two instrumented panels during the ship's voyage off Labrador, Canada, in 1984. The panels were fitted to the ship's bow and tested in a range of different ice conditions. Unfortunately, not a great deal of information is available on the full scale tests nor the detailed measurements that were recorded. However, the general summary of the tests indicated that the friction coefficient was strongly dependent on the normal force and ship speed. The range of normal force recorded was up to about 2,000 N. This corresponds to about 1,785 kPa over the 0.8 by 1.4 m panel. However, the report noted that no analysis of the pressure effects on friction were possible because the actual contact area between the ice and hull was not known.

The results are presented as friction coefficient against normal force. For both panels the friction coefficient tended to reduce from about 0.15 to 0.2 at low normal forces to 0.06 at normal forces of about 1,500 kN (1,339 kPa). Above about 1,500 kN, the friction coefficient tended to remain constant at about 0.06 although more variation in the friction coefficient above 1,500 kN can be seen in the front panel than the shoulder panel. The friction coefficient versus normal force is shown in Figure 2.16 for all the ice conditions documented.

The POLARSTERN data may also be analysed by calculating the tangential force (from the normal force and friction coefficient published in the literature) and plotting this against the normal force. This has been done in Figure 2.17 and results in a linear relationship between the tangential force and normal force with a non zero intercept on the 'y' (tangential force) axis (Tatinclaux 1986).

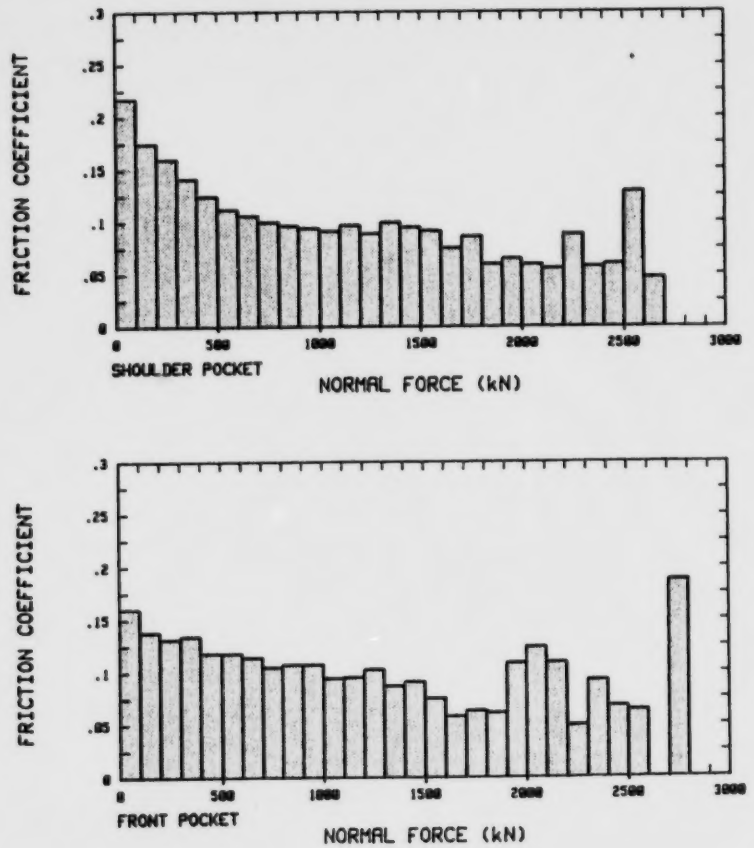
This result is similar to the model tests results (Forland 1985) discussed later in this section. Considering this representation in terms of friction coefficient, it implies that as the normal force or pressure increases, the friction coefficient will decrease to a constant value. The value of the zero normal pressure intercept on the 'y' axis is considered to be a function of the ice adhesion to the surface and thus relates to the type of surface and the ice hardness (Section 2.3 and 2.4).

During the POLARSTERN trials (Hoffman 1986) the ship was tested in a range of different ice conditions from level ice to ramming floes. The results of these tests are shown in Table 2.3. The tangential forces are calculated from the mean normal forces and the friction coefficients given in the report. It may be noted that the broken channel yielded the highest friction coefficient but the lowest tangential force, whilst the pack ice yielded the lowest friction coefficient and the highest tangential force. This would imply that the high friction coefficient associated with the low normal forces may not contribute to the overall resistance as much as the lower friction coefficients associated with the higher normal forces.

A similar series of tests were conducted on the Finnish icebreaking salvage tug PROTECTOR (Enkvist 1985). The ship was fitted with two circular load panels, one on the bow and one on the bottom. The bow panel was 0.26 m in diameter and the bottom panel 1.0 m in diameter. The front

FIGURE 2.16

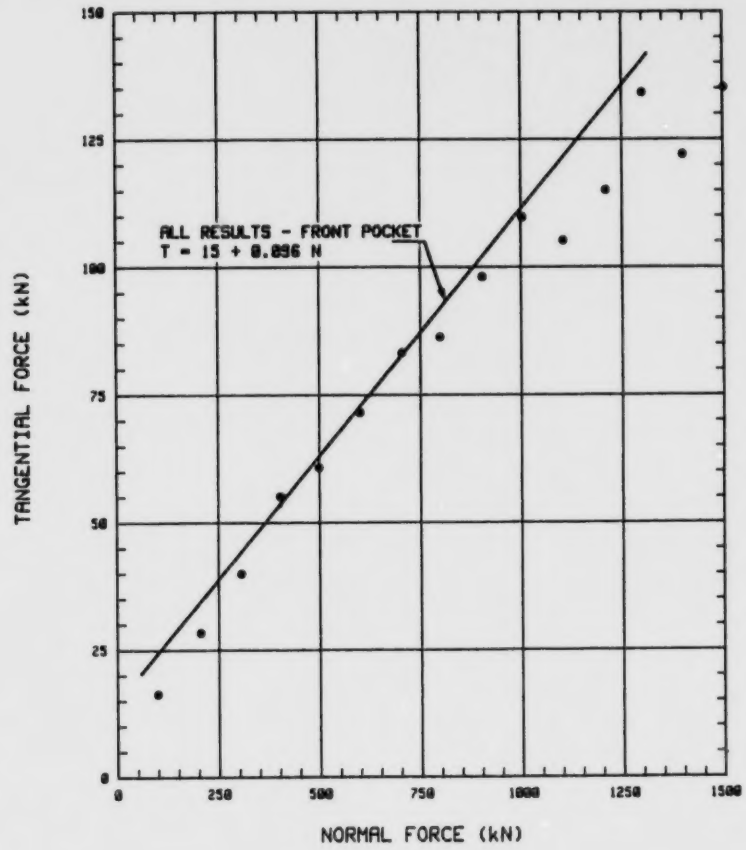
FRICTION COEFFICIENT VERSUS NORMAL FORCE DURING POLARSTERN 1984 TRIALS



FROM HOFFMAN 1986

FIGURE 2.17

TANGENTIAL FORCE VERSUS NORMAL FORCE FROM THE 1984 POLARSTERN EXPEDITION



panel experienced considerably higher normal forces than the bottom panel and resulted in lower calculated friction coefficients. In an old broken channel the bow panel recorded a friction coefficient of 0.045 compared to 0.157 for the bottom panel. In the snow covered level ice the bow panel recorded a friction coefficient of 0.13 compared to 0.255 on the bottom panel. It is also reported that clearing away the snow from the level ice and wetting the snow did not significantly affect these values.

TABLE 2.3

Friction Coefficients and Forces Recorded on the POLARSTERN

	NORMAL FORCE		TANGENTIAL FORCE		FRICTION COEFFICIENT	
ICE CONDITION	Front Cell (kN	Shoulder Cell (kN)	Front Cell (kN)	Shoulder Cell (kN)	Front Cell	Shoulder Cell
Level Ice	386	357	2,354	2,088	0.164	0.171
Broken Channel	141	137	629	479	0.224	0.286
Manoeuvring	306	296	1,636	1,682	0.187	0.176
Pack Ice	278	362	2,172	2,476	0.128	0.146
Ramming	299	263	1,565	1,140	0.191	0.253
TOTAL MEAN	302	339	2,173	2,042	0.139	0.166

from Hoffman 1986

b) Model Scale

Many experiments have been completed on the effects of normal force on the friction coefficient for samples of ice moving against another material. The relationship between normal force and friction coefficient may be expressed as a linear function of frictional shear stress (Tusima 1979; Forland 1985; Arctec 1981):

Shear Stress = (Constant) x Normal Load + Zero Shear Stress

The zero shear stress is defined by the intercept on the 'y' axis of this linear function. Figure 2.18 shows the relationship presented by Forland for a range of different ice hardnesses. The influence of ice hardness on the friction coefficient is discussed in Section 2.4. The zero shear stress is associated with the surface interface and reduces as the

ice hardness increases. For ice hardnesses greater than about 1,500 kPa (85 kPa flexural strength), the 'y' coordinate tends to be negligible and the shear stress becomes constant with increasing pressure.

Oskanen (1980) used a rotating material sample on an ice surface and reported that for a range of material, the friction coefficient for a 115 cm^2 sample decreased to a constant value as the normal force increased to 4 kPa. The tests were conducted using 10 to 50 N weights, yielding pressures from 0.87 to 4.4 kPa, and speeds of 0.5 to 3 m/sec.

The field tests conducted during the POLARSTERN 1984 trials (Tatinclaux 1985) reported that there was no relationship between normal force and friction coefficient. The ice properties during the tests were characterised by weak 250 to 300 kPa ice, so it may have been expected that a non-zero intercept on the 'y' axis of a tangential to normal force relationship would yield a decreasing value of friction coefficient versus normal force. This was reported not to be the case.

2.6 Relative Sample Speed

a) Full Scale

During the full scale tests of the POLAR STAR (Arctec 1982), the radial arm equipment was used to record the friction coefficient as a function of normal force and average speed. Figure 2.19 presents the data as friction coefficient versus average velocity. The normal force was adjusted from 1,148 N (258 lb) to a maximum of 5,743 N (1,291 lb). It can be seen from the figure that there was no significant trend with average speed. It should also be noted that, although problems were reported with the operation of this equipment, the highest coefficient of friction, 0.343, represents a significantly higher value than generally observed, and highlights the potential range that may be achieved on hull surfaces.

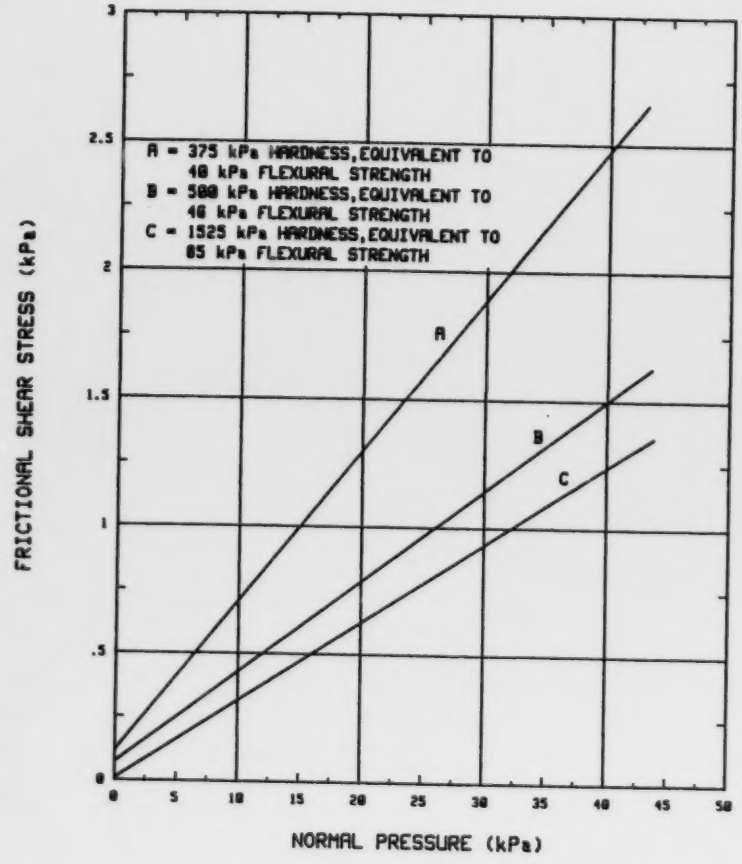
The POLARSTERN was tested in 1984 in level ice conditions and the results indicated a different speed relationship for the two instrumented panels. The forward panel did not demonstrate any dependency between friction coefficient and speed and tended to remain constant over the range of zero to 12 knots. The shoulder panel, over the same speed range, showed the friction coefficient increasing linearly with speed. The tests were not able to determine whether this difference in relationship was due to the different normal forces occurring on the two panels or the different ice/hull interaction that was occurring in the two locations.

Unfortunately, there was no analysis of the effect of speed on the full scale results of the PROTECTOR to compare with the POLARSTERN data.

During the 1978/79 test of the RADISSON, the swinging arm device was used to measure the hull friction coefficient (Arctec 1979). Results from the tests indicated that the friction coefficient was independent of speed above about 1.0 m/sec. Similar results were reported for other tests (Arctec 1982).

FIGURE 2.18

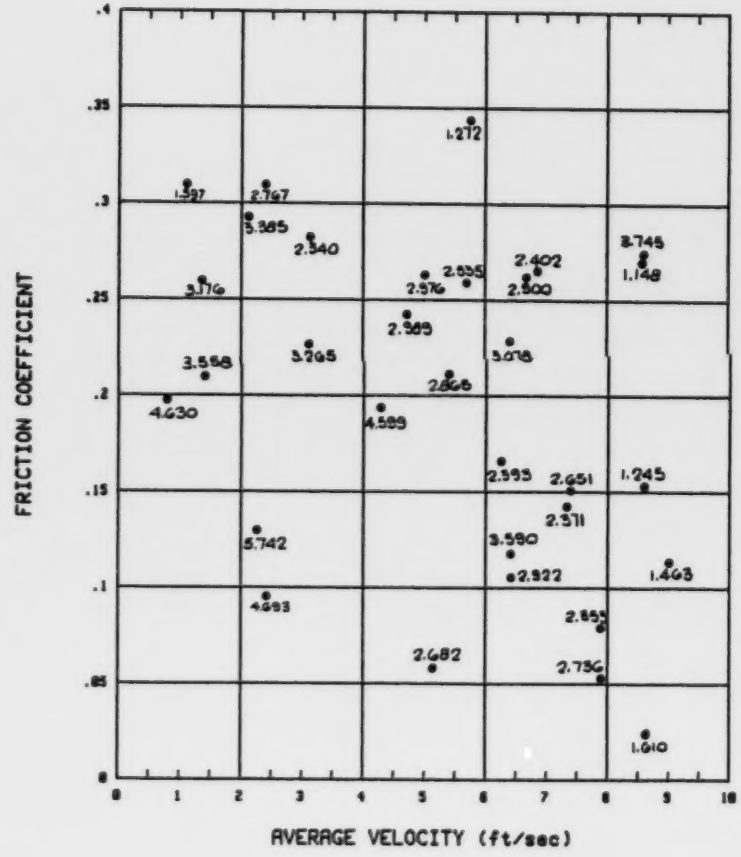
FRICTIONAL SHEAR STRESS AS A FUNCTION OF NORMAL PRESSURE



FROM FORLAND 1985

FIGURE 2.19

POLAR STAR, 1982 ROTATING ARM MEASUREMENTS



NORMAL FORCE = kN
FROM ARCTEC 1982

b) Model Scale

Model tests investigating the effect of speed on the friction coefficient have been completed for both samples of ice moving on a material and a sample of material moving on ice. In the case of a sample of ice moving on a smooth material (0.36 μm RA), the friction coefficient tends to increase with speed (Forland 1985), and is shown in Figure 2.20. This is believed to be due to the dissipation of the frictional heat. The ice sample moving over the material is being continually warmed and builds up a layer of melt water at the surface interface. This increased water layer will increase the viscous shear stresses which will add to the friction coefficient and may become the predominant source of resistance (Oksanen 1980).

When a smooth (0.33 μm RA) material slides over an ice surface, the friction coefficient has been shown to not vary significantly. This is thought to be due to the constantly changing ice interface with the material and, therefore, there is no time for the ice to melt and the interface does not develop the water layer.

It is interesting to note that at low speeds the friction coefficient for the two configurations is about equal. This indicates that, at low speeds, the frictional heat has insufficient to develop a melt water layer between the ice and material.

Unlike the smooth material, in the case of a rough material (roughness 1.5 μm RA) sliding over ice, the friction coefficient varies with speed, as shown in Figure 2.21.

The reason for this is believed to be due to the penetration of the melt water layer by the material asperities. As the velocity increases, the voids between the asperities tend to fill and the friction coefficient is reduced, as shown in the figure.

Similar trends were reported during the tests conducted in conjunction with the POLARSTERN trials in 1984 (Tatinclaux 1985). For samples of dry ice on Inerta painted steel (roughness 0.97 μm CLA), no variation of friction coefficient with speed was recorded. For the roughened Inerta plate (roughness 3.00 μm CLA), the friction coefficient at low speeds was significantly higher and reduced with increasing speed.

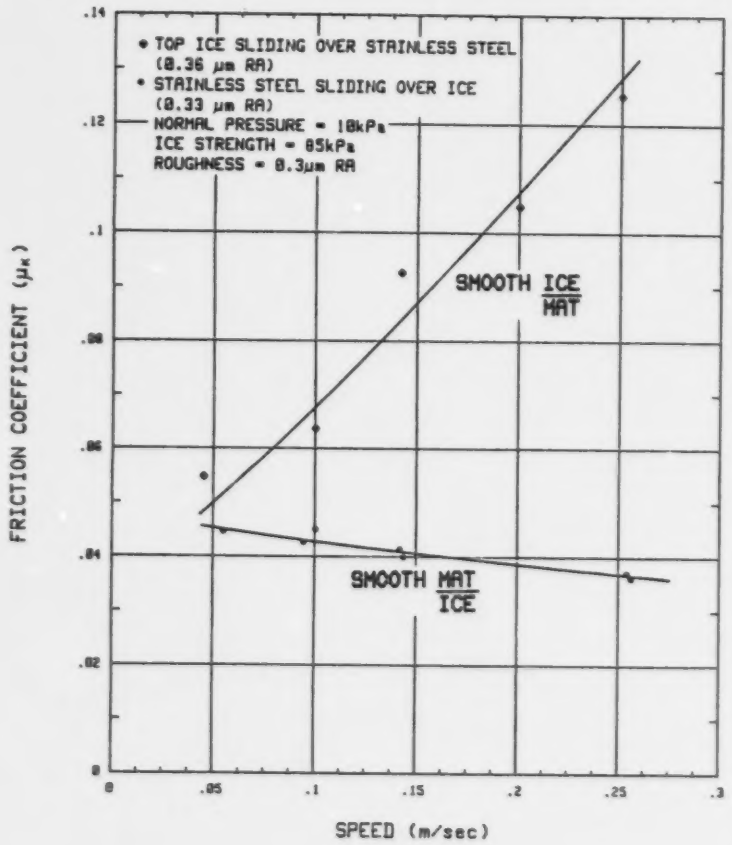
2.7 Model Tests

Although the friction coefficient has been recognised as having a significant effect on the resistance of ships and models, it has not been the subject of any focused series of model test programmes.

Model tests have been conducted on the POLAR class icebreakers (Lecourt 1978) at four friction coefficients, 0.01, 0.1, 0.3 and 0.5. The data from the test programme was put into a regression analysis and prediction equations were generated for each hull surface. Figure 2.22 presents the model test results as percentage increases or decreases in resistance from 0.1.

FIGURE 2.20

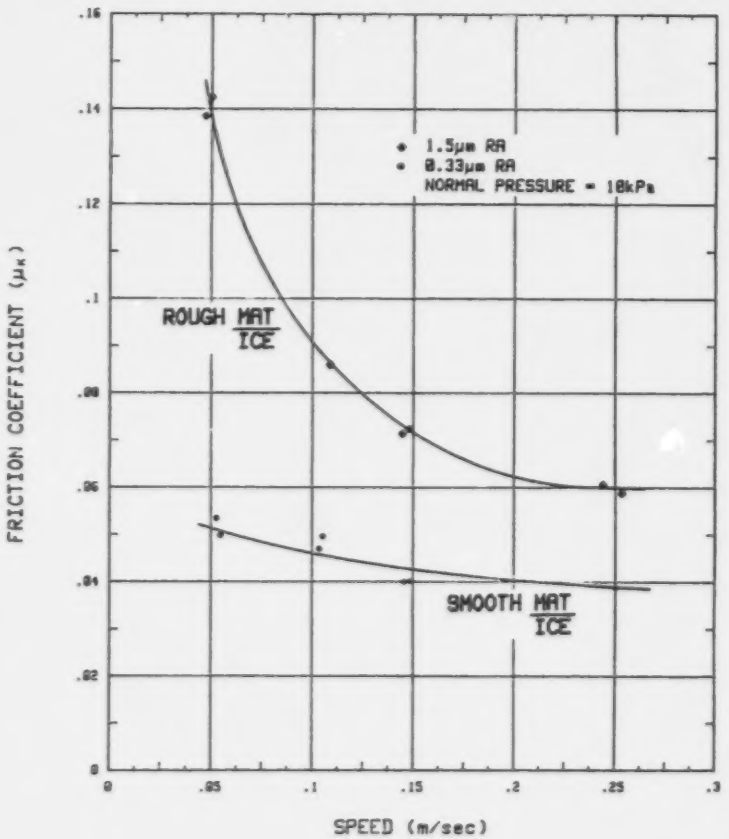
EFFECT OF SPEED AND TEST CONFIGURATION ON FRICTION COEFFICIENT



FROM FORLAND 1985

FIGURE 2.21

EFFECT OF ROUGHNESS AND VELOCITY ON THE FRICTION COEFFICIENT



FROM FORLAND 1985

speed range shown. The smoother models do not demonstrate the same trend and this is compatible with the results of the sample testing of a rough sample sliding over ice, discussed in Section 2.6.

A typical influence curve of friction coefficient and model resistance was presented by Makinen (1975) and is shown in Figure 2.23. Unfortunately neither the type of vessel nor the speed range for the model tests is presented, so very little can be deduced from the data. However, comparing Figure 2.22 and Figure 2.23, the Makinen result shows a stronger dependence of resistance on friction than the Lecourt data.

Model tests conducted as part of the SS MANHATTAN Arctic marine project (Arctec 1970) investigated the effect on resistance of changing the friction coefficient on the bow and midbody and concluded that the ice/hull friction was the most dominant component of the resistance and that the resistance of the model was influenced significantly more by the bow than the midbody.

2.8 Summary

The basis for model experiments is that the mechanical and physical phenomenon of ice breaking can be simulated at model scale. This overall assumption applies to every aspect of model testing, however, the reality is that the model is not fully representative of full scale. This is generally known and may be accepted provided that those aspects of the model that are not representative do not have a significant effect on the model performance, or, if they do they, the errors can be correctly quantified and adjustments made to the model test results.

The literature review has confirmed that the influence of the friction coefficient on the performance of icebreakers at model and full scale is significant.

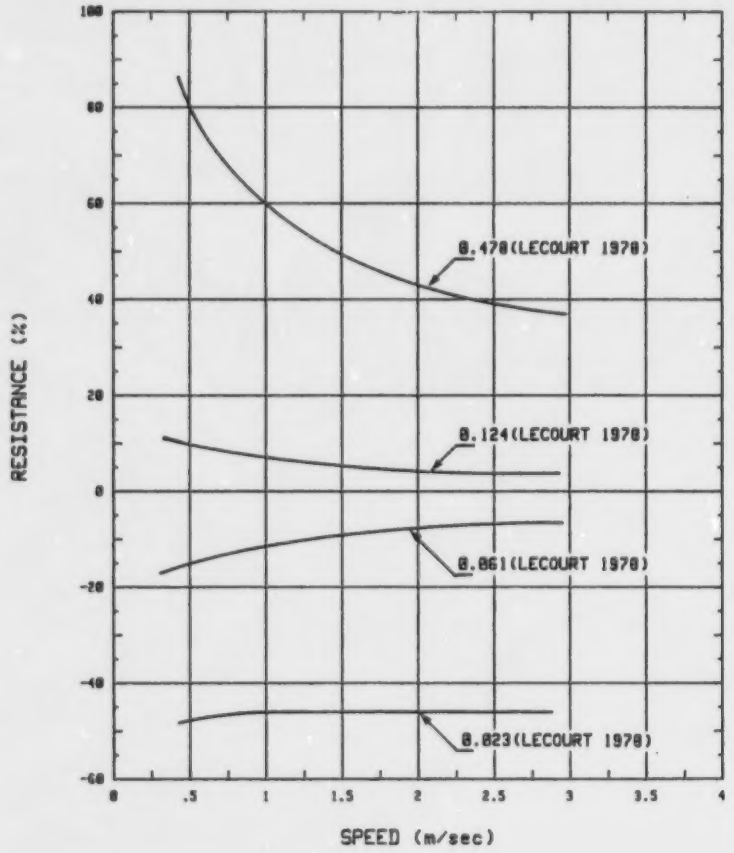
Full scale tests have indicated that the friction coefficient is a function of the mechanical and physical properties of the ice and contacting material. They have also indicated that the predominant effect of friction at full scale is due to the higher friction forces associated with lower friction coefficients, rather than the lower friction forces and resultant higher friction coefficients. Model scale tests have identified that similar trends exist for the equivalent model scale variables. The preceding review has identified the majority of these variables and, although their is some consensus on the dependence of the friction coefficient on these variables, there is no evidence to indicate whether the values used at model scale are representative of the phenomenon at full scale.

There are a number of observations that can be made in relation to this problem of model to full scale correlation:

1. The available information on the effect of the friction coefficient at full scale is very limited.

FIGURE 2.22

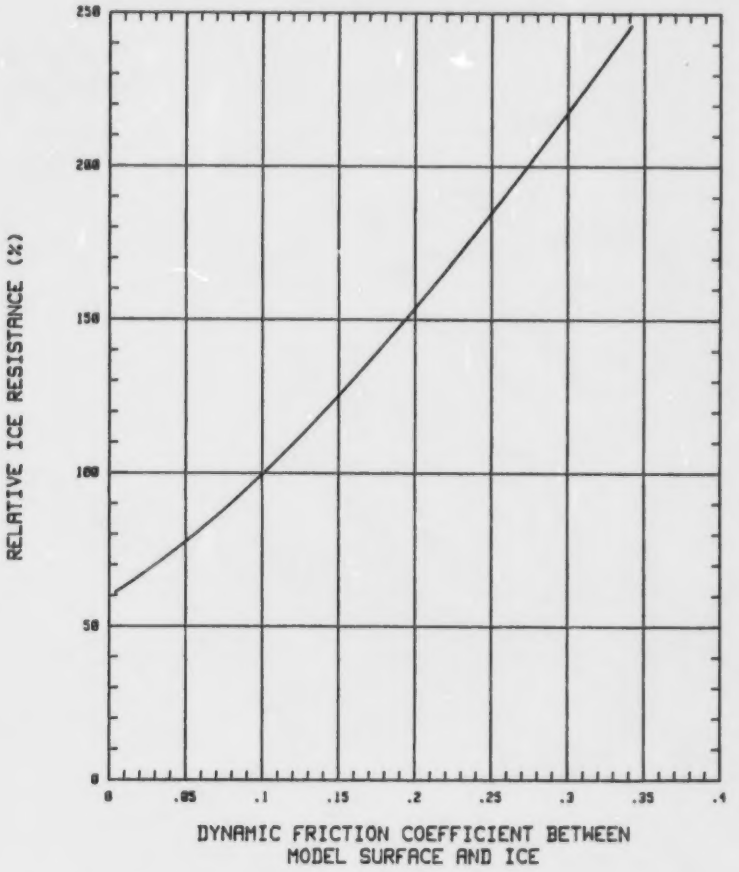
RESULTS OF MODEL TESTS USING
FOUR DIFFERENT FRICTION COEFFICIENTS



FROM LECOURT 1978

FIGURE 2.23

TYPICAL CURVE SHOWING INFLUENCE OF
FRICTION COEFFICIENT ON RESISTANCE



FROM MAKINEN 1975

2. The absolute value of the full scale friction coefficient is believed to vary as a function of the way in which it was measured, the normal forces, the ice condition and the ice sample velocity and configuration.

3. The mechanical interaction between the ice and the hull represented as the friction coefficient has only recently been addressed by instrumenting the bow of two icebreakers. Unfortunately very little information has been made available on either of these experiments.

4. The normal and tangential forces associated with the values of friction measured at full scale are considered to be significantly higher than the equivalent model scale values.

5. It has generally been accepted, we believe incorrectly, that because the friction coefficient is non-dimensional it does not exhibit a scale effect.

The work completed to date has not solved these problems and as a result their influence on the performance prediction of an icebreaking ship from model tests must be considered.

3. SURFACE DEFINITION TESTS

3.1 General

The objective of the model test programme is to investigate the influence of different model surfaces on resistance. This required the development of a number of different paint systems that would produce uniform and consistent surfaces. Each paint system was tested using a sample panel, coated with the specific paint formulation, and a friction jig which was designed and built at IMD. The test equipment and procedure to investigate the different surfaces were selected after a review of existing methods. The final design of the friction jig was developed by IMD with the assistance of Dr. Kitagawa of the Japanese Ship Research Institute, who was resident at IMD during the test period.

This section of the report summarises the equipment used and the surface definition tests conducted on the different paint coatings and compares the results with data from other similar test programmes discussed in Section 2.

3.2 Friction Jig and Sample Preparation

The equipment used to measure the friction coefficient of the sample panels is shown in Figure 3.1 and Figure 3.2.

FIGURE 3.1

EQUIPMENT USED TO MEASURE FRICTION COEFFICIENT

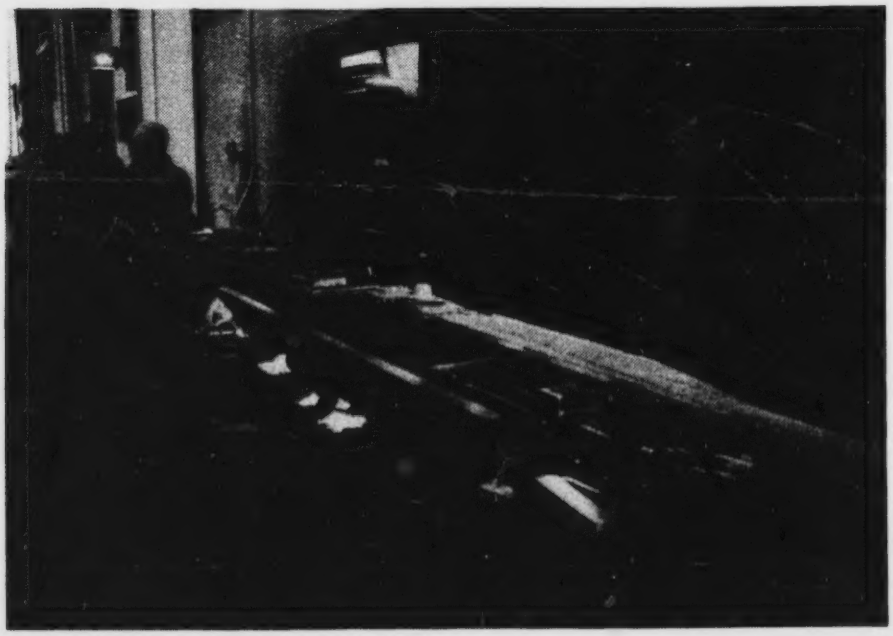
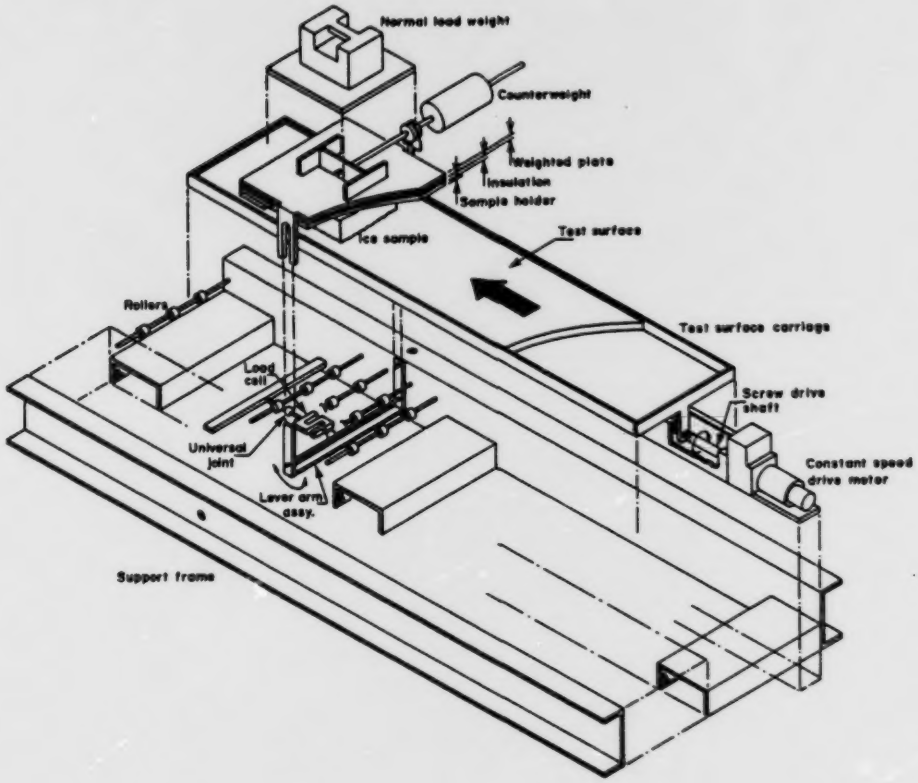


FIGURE 3.2

SCHEMATIC OF FRICTION JIG USED AT IMD



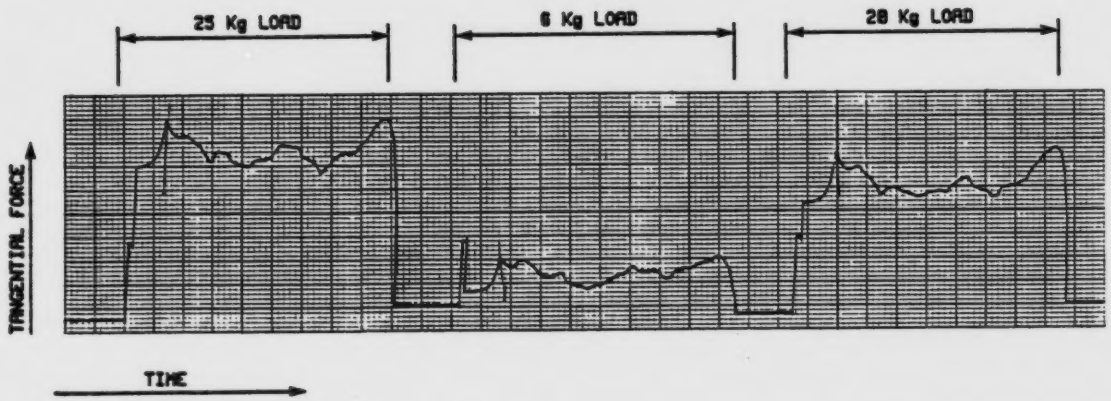
The test apparatus consisted of a sample holder, onto which the ice sample was attached. This is supported vertically using a fulcrum and counterweight and restrained in the longitudinal direction by a horizontal fulcrum and load cell. The test material is positioned below the ice sample in a tray that can be driven longitudinally beneath the ice sample by an electric motor and screw drive. The longitudinal motion of the test material is resisted by the loaded ice sample and recorded using the load cell. This longitudinal resistance to motion is considered to be the tangential friction force between the ice sample and material. The equipment is calibrated by suspending standard weights from the ice sample holder and over a pulley at the end of the test jig.

The tangential force from the load cell was displayed on a chart recorder and calibrated to yield tangential force in Newtons. An example of the friction jig output is presented in Figure 3.3 and the detailed output from each friction test conducted is presented in Appendix 2.

A number of different sample finishes were investigated, including acrylic lacquers and epoxies. A detailed discussion of the surface finishing techniques is given in Appendix 3.

FIGURE 3.3

SAMPLE OUTPUT FROM FRICTION JIG



3.3 Test Description

The majority of the sample friction tests were conducted simultaneously with the model friction tests. In addition, to increase the number of sample test runs, a number of the tests were also conducted in association with other test programmes at IMD.

Although the tests procedure varied slightly from test to test the same overall test plan remained the same, as follows;

1. Prior to the test, the sample ice holder was placed in a cold room with an internal temperature of about -20°C, which was directly adjacent to the ice tank.

2. At some time during the model test, a hand held saw was used to cut a 0.14 square meter sample from the ice sheet.

3. The ice sample was immediately taken to the cold room and frozen to the sample holder using fresh water.

4. The sample and sample holder were then taken to the friction jig and positioned over the material sample.

5. The counterweight was adjusted to balance the sample holder so that there was zero vertical force on the material sample.

6. The material sample was wiped dry.

7. Using a succession of increasing weights, the ice sample was loaded and the material dragged beneath it at a constant speed of 25 cm/sec.

8. Following each day's tests, the instrumentation was calibrated with standard weights.

The range of normal loads on the ice sample were 2, 5, 10, 15 and 20 kg. Nominal pressures on the 0.14 m sample were therefore 1, 2.5, 5, 7.5 and 10 kPa.

Two different surface preparations were used for the test programme. Three lower friction coefficients were created using an epoxy coating called Imron, with a number of additives to modify the surface characteristics. Table 3.1 lists the components of the paint used for each surface finish. An additional high friction coefficient surface was created by laying a coarse fibreglass mat on the surface of the model.

TABLE 3.1

Components of Paint Used for Each Surface Finish

	Surface 1	Surface 2	Surface 3
Imron A	2 quarts	2 quarts	2 quarts
Imron B	1/2 quarts	1/2 quarts	1/2 quarts
magnesium silicate	-	400 gm	400 gm
catalyst	14 gm	14 gm	14 gm
thinner	200 gm	200 gm	200 gm
air gun pressure	50 psi	50 psi	50 psi
flattening agent	-	300 gm	300 gm

From IMD Report Williams 1986

3.4 Results

The friction coefficient has been defined by the following relationship;

Tangential Force = Friction Coefficient x Normal Force + Offset

The results from the sample test programme are presented as normal force versus tangential force. The form of this relationship, which is defined by drawing a straight line through the data, yields the offset.

The initial programme was intended to consist of three hull surfaces with a middle friction coefficient of 0.1. Unfortunately the "rough" surface resulted in a friction coefficient of only about 0.06. As a result it was decided to re-test another sample panel and bow section with a significantly rougher surface finish.

Eight model surfaces were tested, represented by five panels, the results of these tests are presented in Figures 3.4, 3.5, 3.6, 3.7 and 3.8, for the five friction coefficients tested. The Figures show the normal versus tangential forces recorded during the experiment and the data complies with the results obtained from other researchers discussed in Section 1. The form of the data consists of a linear relationship with either a positive or negative offset. The offset appears to vary outside the controlled parameters of these tests and has been attributed to the particular physical and mechanical properties of the ice. These may have varied slightly for each experiment whilst the ice remained within the control parameters of the overall test strength and surface texture criteria. The derivative of the linear equation representing each set of data for each panel remains reasonably constant and this supports the form of the friction coefficient equation defined above.

In addition to the presentation of tangential force versus normal force, this type of data may also be presented as friction coefficient versus normal force. This has been done for the five test surfaces and is presented in Figures 3.9, 3,10, 3.11, 3.12 and 3.13. Comparing this data with the experiments by previous researchers (e.g. Forland 1986) confirms that the friction equipment and test procedures are compatible with current research standards.

The friction coefficient for each panel has been obtained by taking the mean of the friction coefficients calculated from each surface. This results in the values shown in Table 3.2. These values have then been attributed to the respective model segment in the following section.

In addition to the calculation of friction coefficient, the test surfaces were also measured with a Taylor-Hobson surtronics profilometer. This equipment measures the roughness average as a centre line average (CLA) in micromillimeters.

FIGURE 3.4

SURFACE - 1
TEST PANEL RESULTS

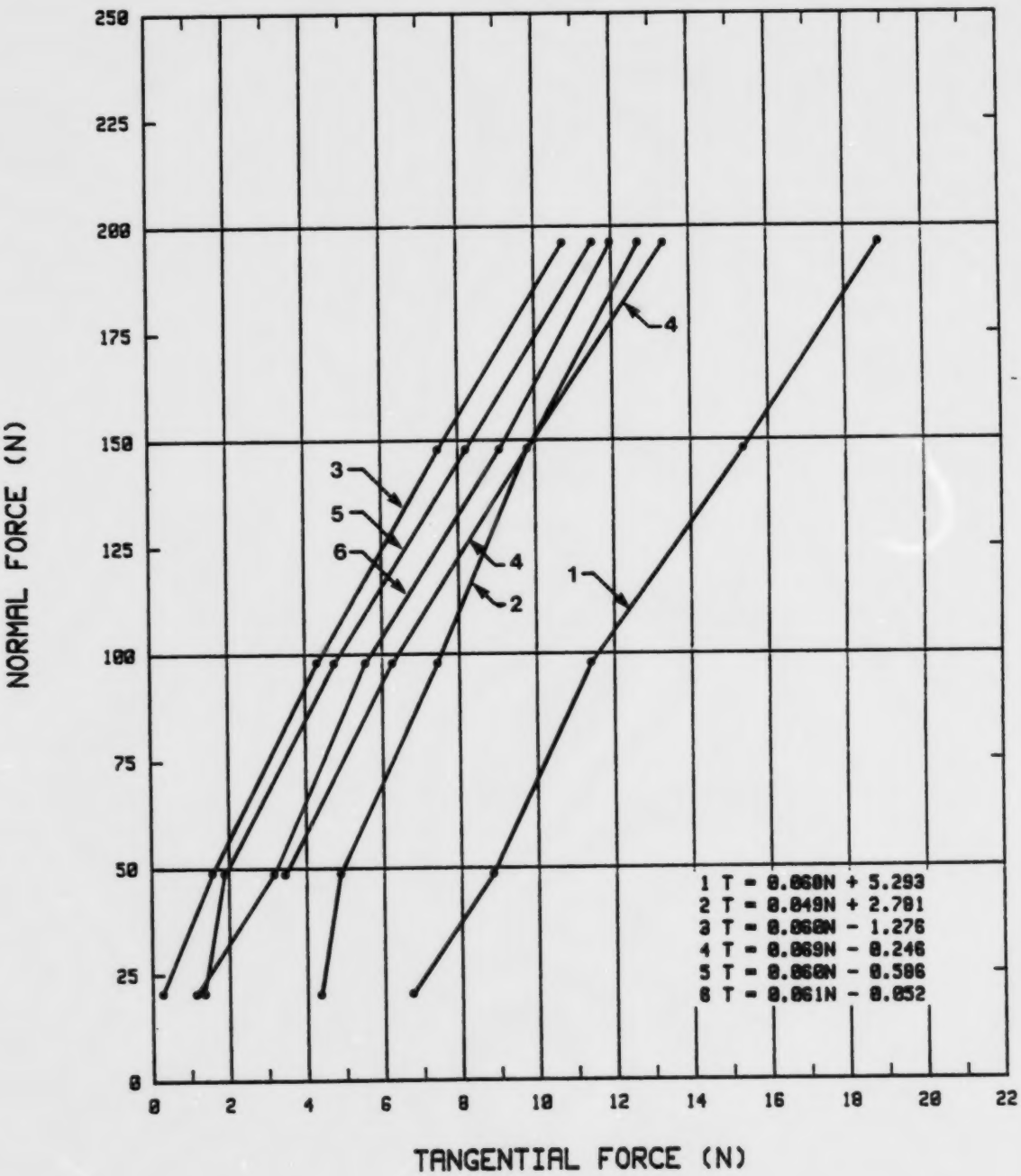


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FIGURE 3.5

SURFACE - 2
TEST PANEL RESULTS

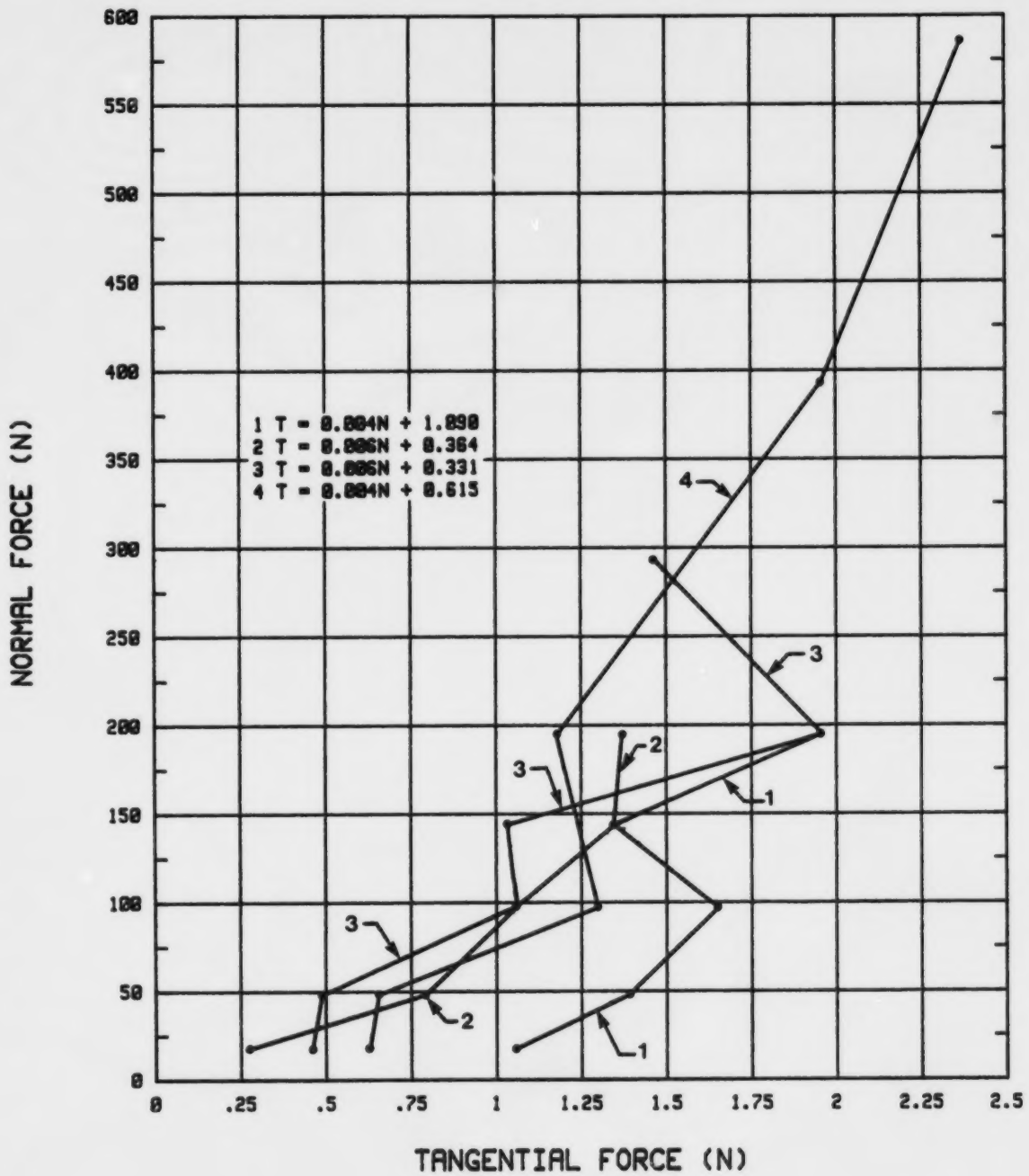

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FIGURE 3.6

SURFACE - 3
TEST PANEL RESULTS

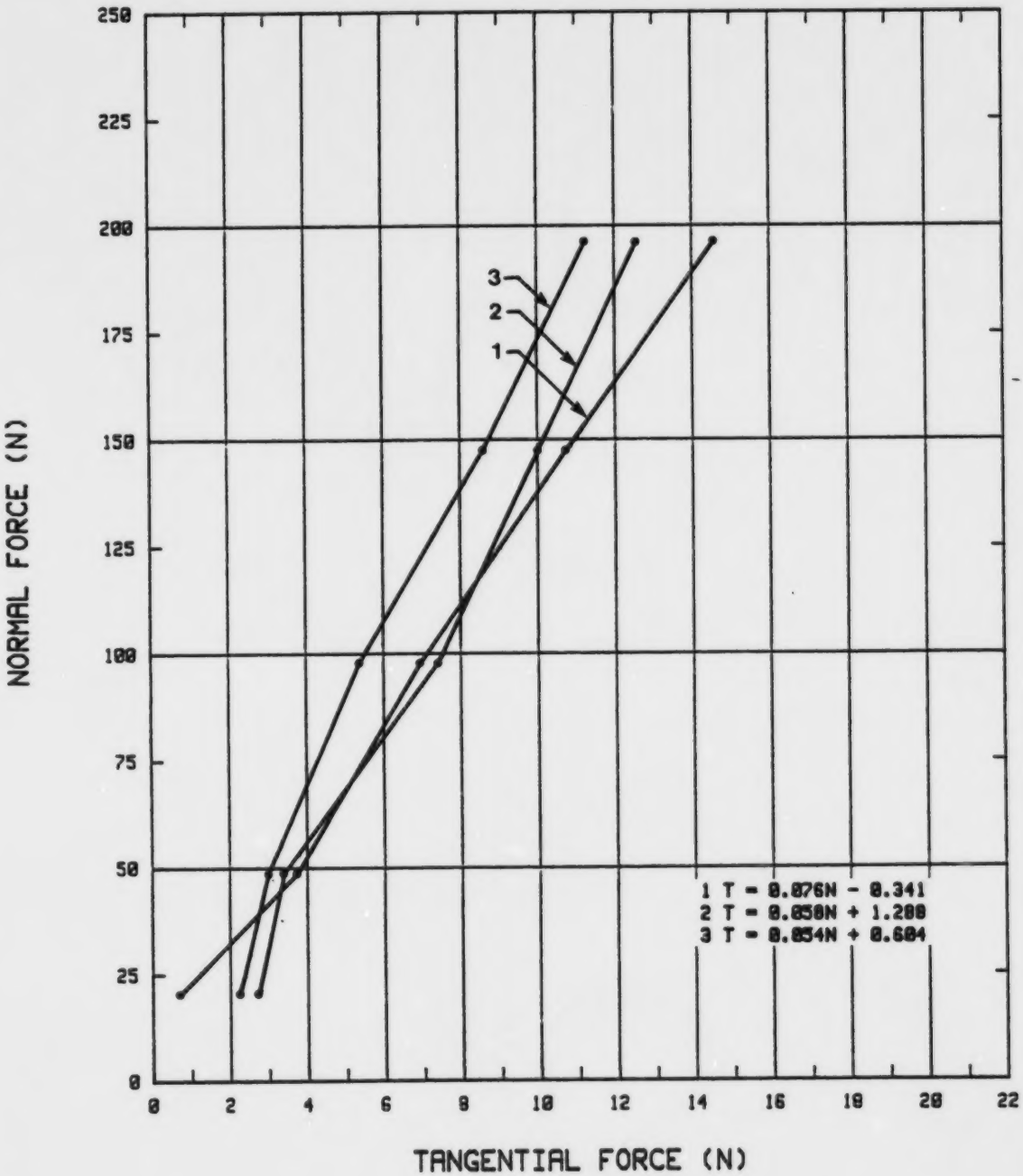

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FIGURE 3.7

STERN
TEST PANEL RESULTS

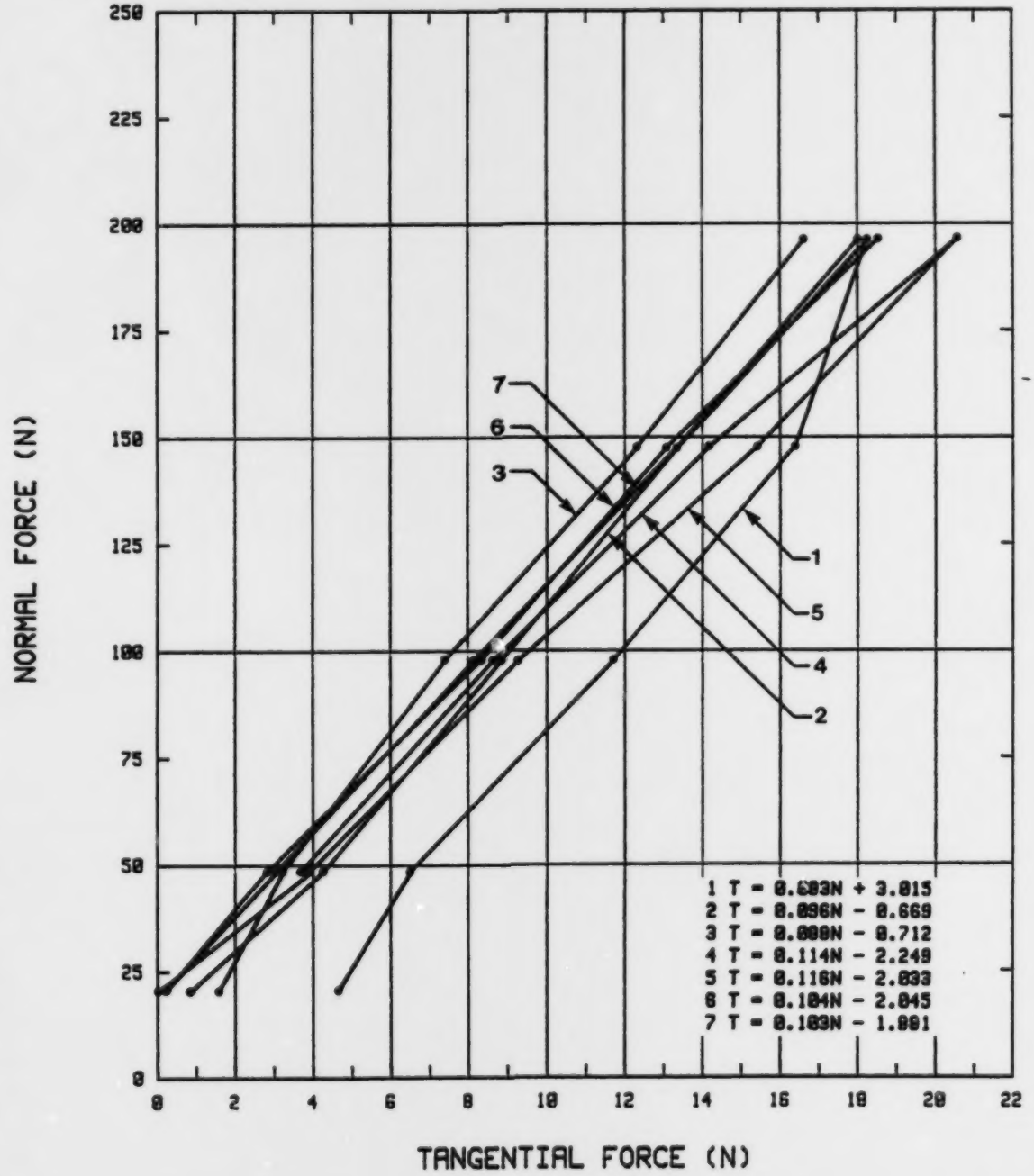

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FIGURE 3.8

SURFACE - 4
TEST PANEL RESULTS

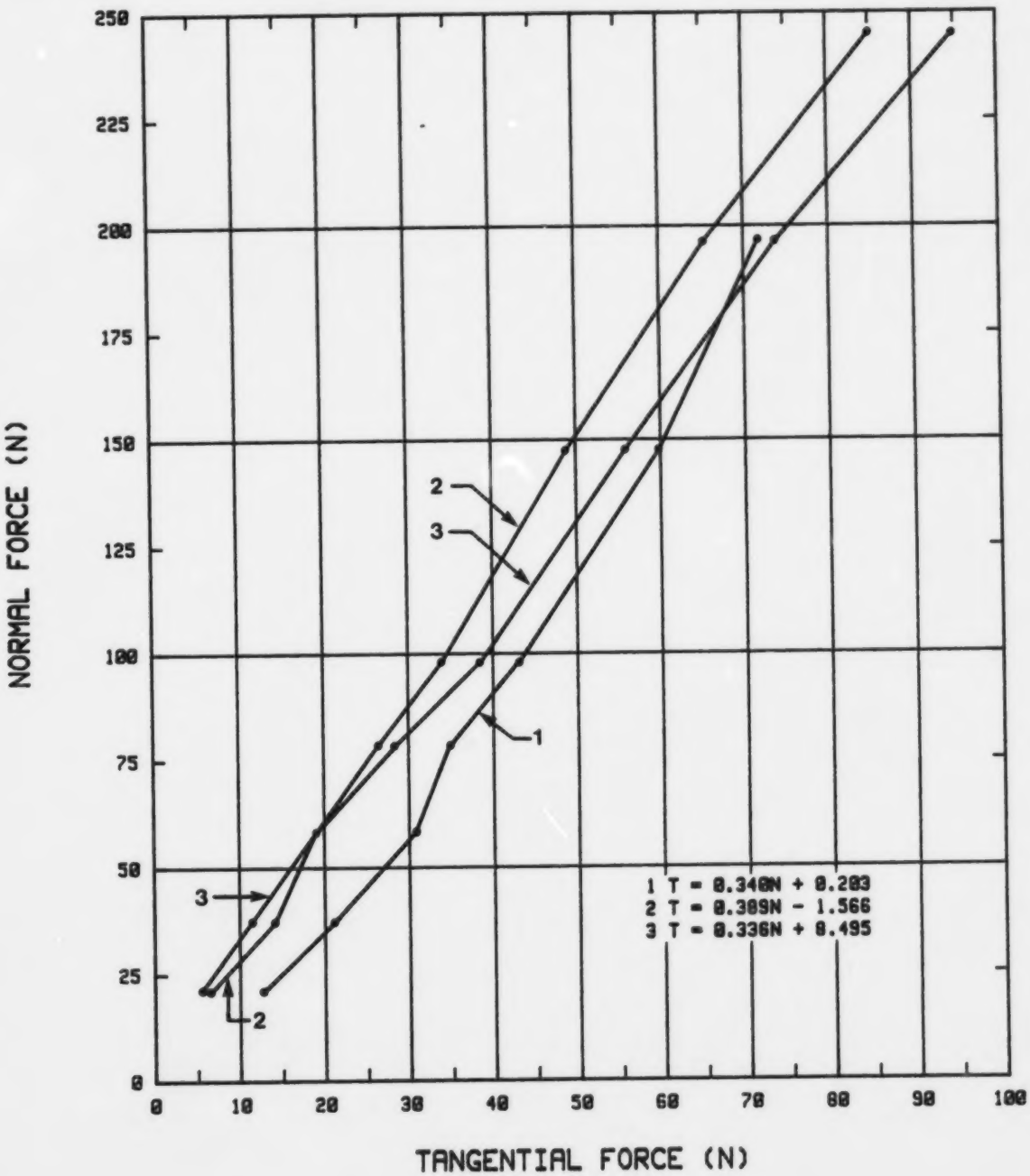

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FIGURE 3.9

SURFACE - 1
FRICTION VERSUS NORMAL FORCE

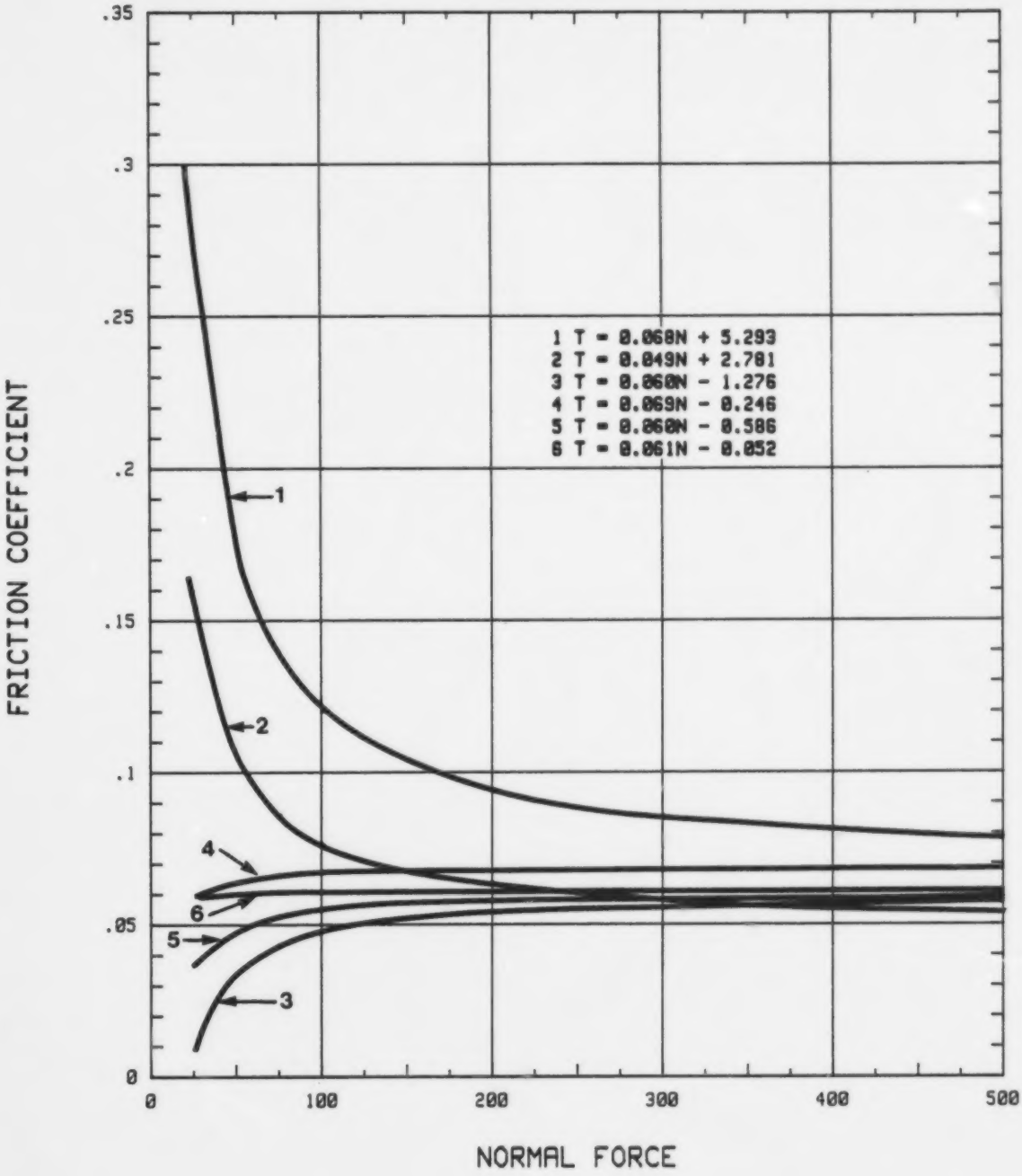

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FIGURE 3.10

SURFACE - 2
FRICTION VERSUS NORMAL FORCE

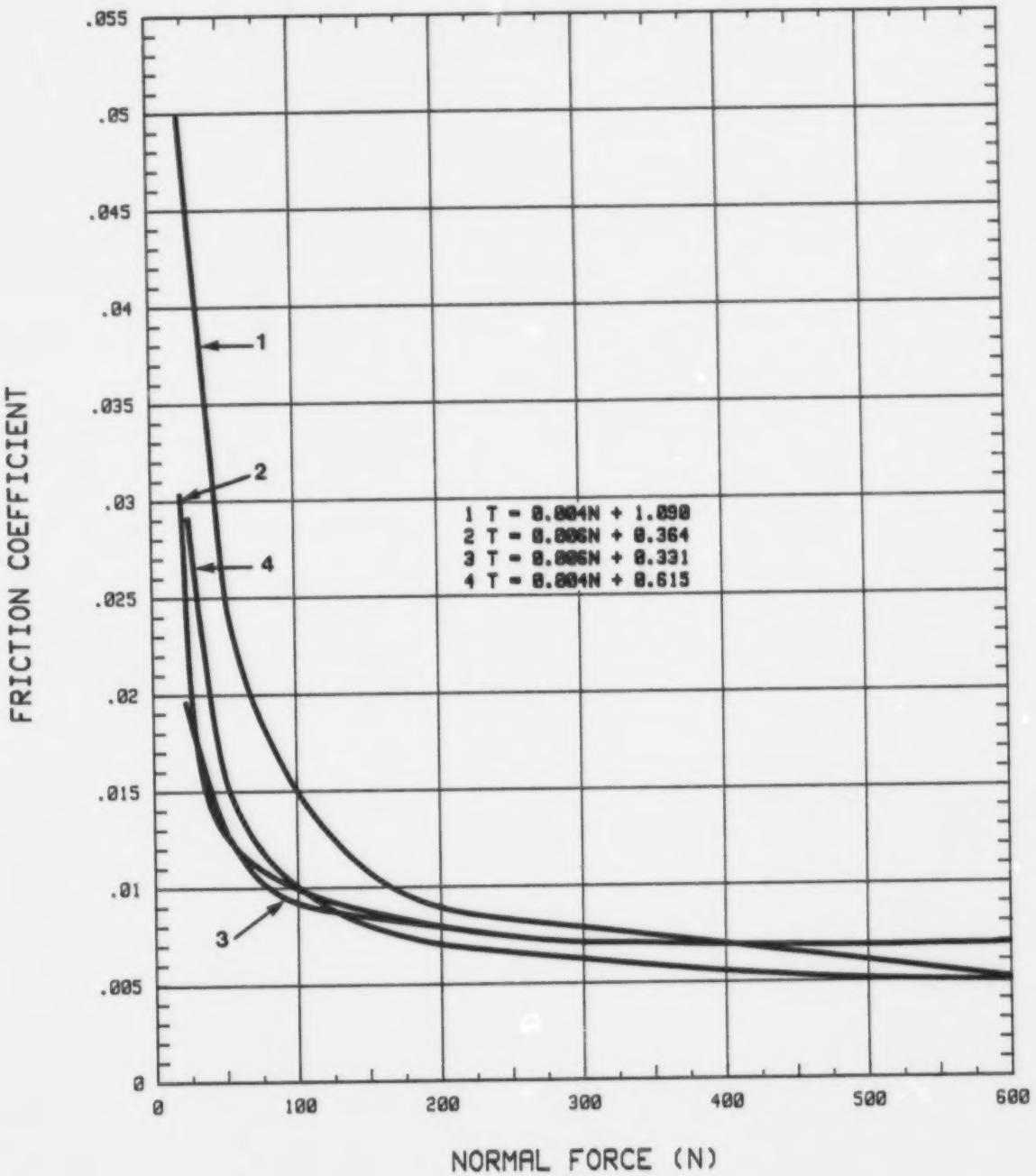

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FIGURE 3.11

SURFACE - 3
FRICTION VERSUS NORMAL FORCE

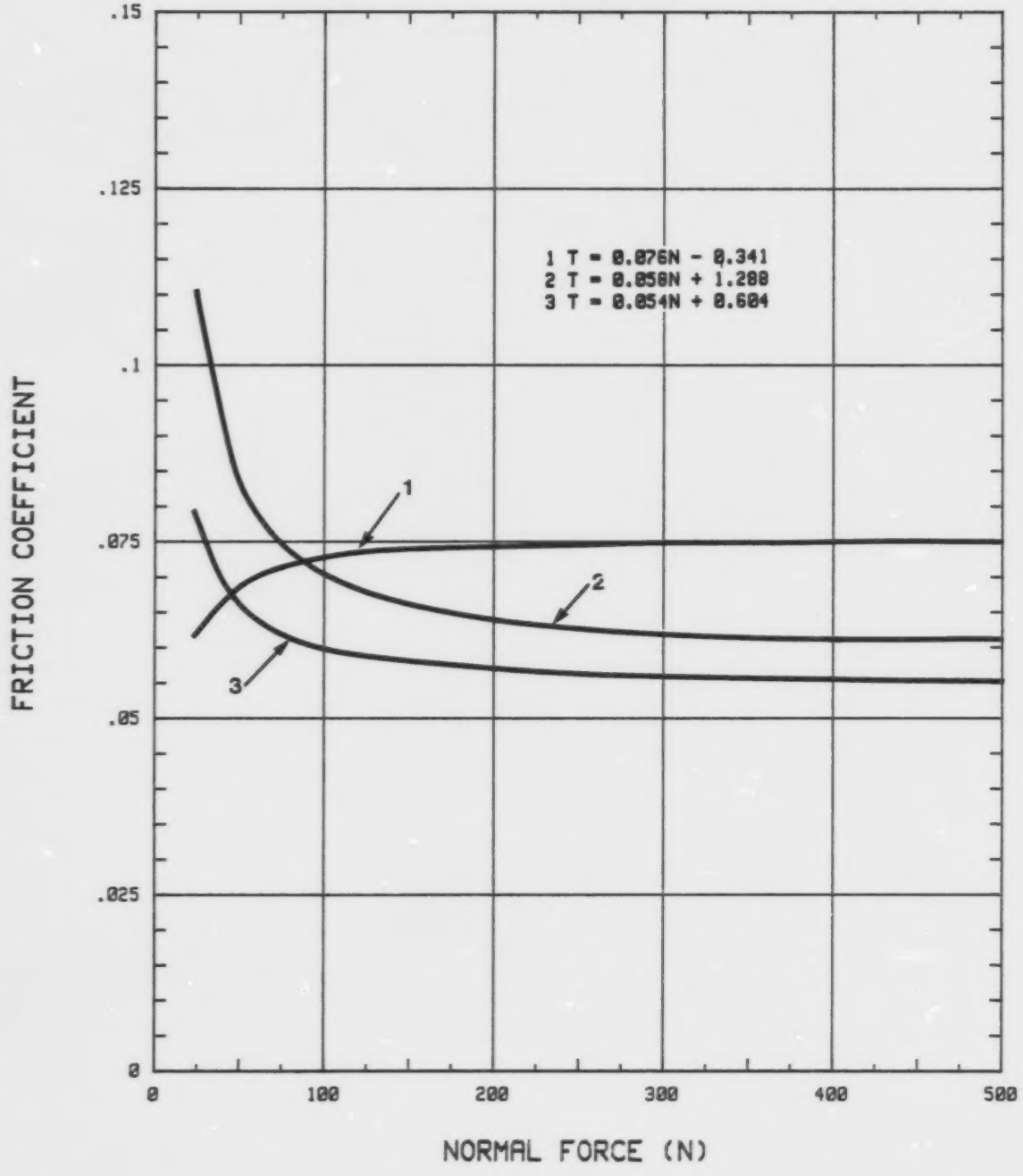

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FIGURE 3.12

STERN
FRICTION VERSUS NORMAL FORCE

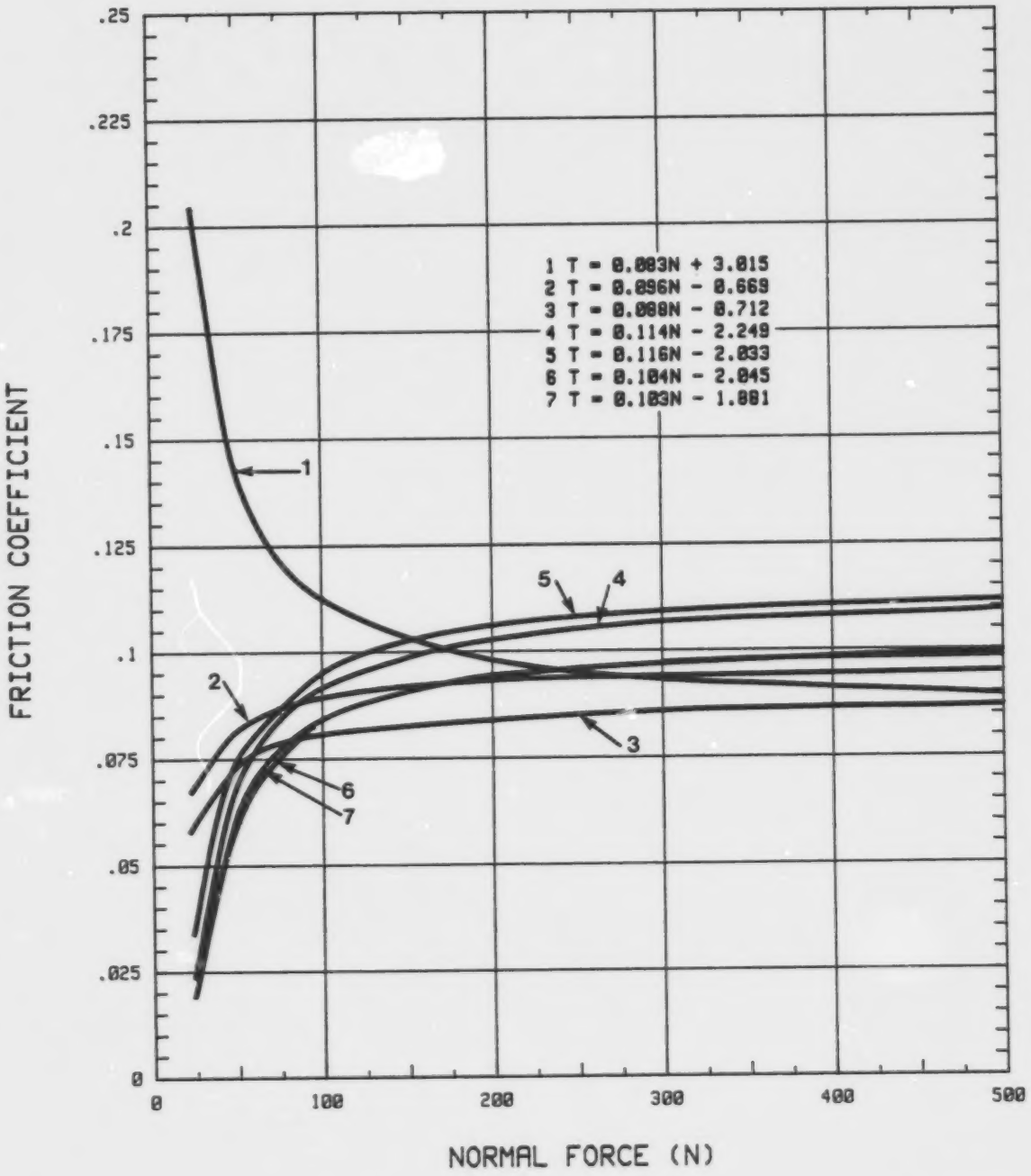

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FIGURE 3.13

SURFACE - 4
FRICTION VERSUS NORMAL FORCE

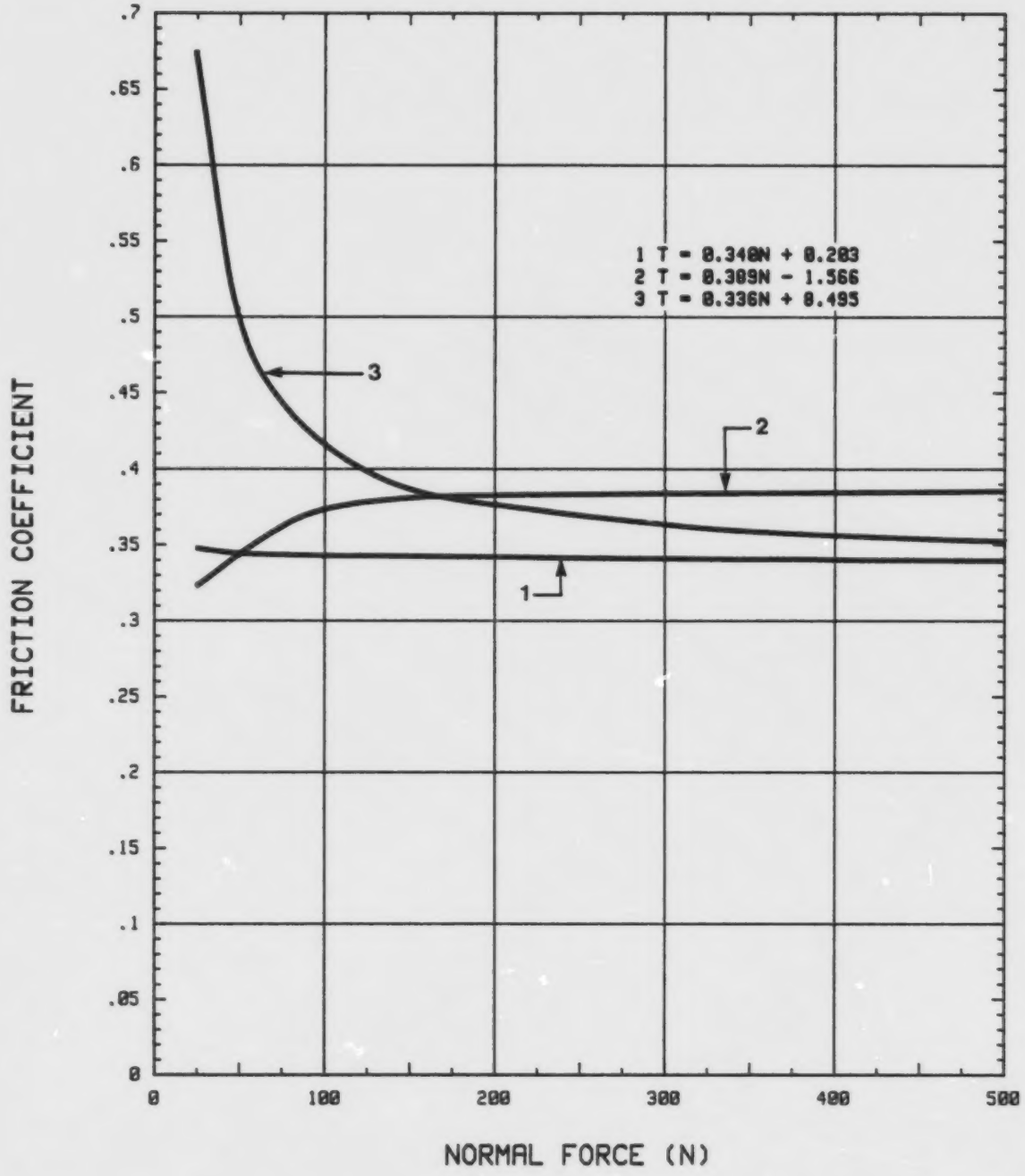

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TABLE 3.2

RESULTS OF THE FRICTION COEFICIENT PANEL TESTS

Panel	Number of Tests	Average Friction Coefficient	Standard Deviation
Stern Section	7	.100	.0124
Panel #1,	6	.061	.0072
Panel #2,	3	.004	.0012
Panel #3,	3	.065	-
Panel #4	3	.354	.295

4. MODEL TESTS

4.1 General

The model tests were conducted at the ice tank of the Institute for Marine Dynamics in St. John's Newfoundland. Details of the ice tank and the facility have been published in the literature (Jones 1986). The model consisted of seven parts; three bows, three midbodies and one stern. Each part was prepared with a different surface preparation as described in the previous section. With the exception of the stern, which was made of wood, the model was constructed from fibreglass laid over a foam mould. This is now a standard model fabrication technique used at the IMD.

The model was a 1:30 scale reproduction of the ARCTIC, an Arctic Class, 28,000 tonne DWT OBO carrier. The model tests consisted of 11 towed resistance tests in model EG/AD ice (Timco 1985) representative of 1.5 m, 570 kPa full scale ice. An additional test was also conducted in an equivalent 1.2 m ice sheet to investigate the effect of ice thickness and to compare with results from previous model tests (Baker 1986). These ice thicknesses and strengths correspond to 50 mm and 40 mm, 19 kPa model ice. The ice strength is nominally higher than would have been preferred but was selected to ensure consistent strength, which is difficult to obtain with weaker ice.

Reference will be made throughout this section to surfaces 1 to 4. In all cases surface 1 is the middle roughness surface with a friction coefficient of 0.061. Surface 2 is the very smooth surface with a measured friction coefficient of 0.004. Surface 3 is the original rough surface which resulted in a similar roughness to the middle roughness and has a nominal friction coefficient of 0.065. Surface 4 is the very rough surface with a friction coefficient of 0.354.

Details of the ice testing and results are presented in the following sections.

4.2 Model Test Programme

The model test programme may be divided into two parts. The first part was conducted between September 1986 and February 1987 and consisted of the three lower friction coefficients. Following a review of these tests it became apparent that additional tests were required with a rougher friction coefficient. These were conducted in October 1986.

The programme was conducted using standard test procedures and generally consisted of:

- ice flexural strength and elastic modulus recorded prior to the model test,
- continuous model tests at four target speeds: 0.19, 0.33, 0.47 and 0.6 m/sec corresponding to 1, 1.8, 2.5 and 3.3 m/sec at full scale,

- ice sheet thickness and flexural strength measurements,

- preparation for the presawn ice tests consisting of "stapling" the existing broken ice sheet and floe cutting.

- presawn ice test at the same speeds as the first set of tests down the south side of the ice tank,

- Flexural strength measurements.

A summary of the total test programme is presented in Table 4.1. The results of the test programme are presented in Table 4.1. The table is extracted from Melville's standard model test analysis program and presents in the first four columns the ice sheet number, and the measured ice thickness, strength and model speed. The fifth column presents the resistance data. If this has been corrected, then the column will show corrected data. Any correction applied is shown in the sixth column. The seventh column is the ice sheet identifier used in the program. If the same model is run twice then the description may include a prefix, for example 'T' for thinner ice, or '1' and '2' for successive tests. The note column identifies any variations in the standard model test correction procedure and is described at the bottom of each page and a detailed presentation of the test method and data may be found in Appendix 2.

4.3 Model Test Results

The model test results represent a total of twelve ice sheets and may be presented in a number of combinations. For the purpose of this report the three combinations of hull sections and friction coefficient will be compared against the base case of Surface 1 on the bow and midbody. However the data presented in Table 4.1 does not consist of a single ice strength or thickness and as a result corrections should be made to the data that will normalise each data set. To more clearly define and describe the data analysis the following section is subdivided into a number of subsections which are;

a) Data overview; A review of the data collected, its overall consistency and the level of confidence that can be placed in the results.

b) Data correction; The normalisation of the data to a common ice thickness and strength for analysis

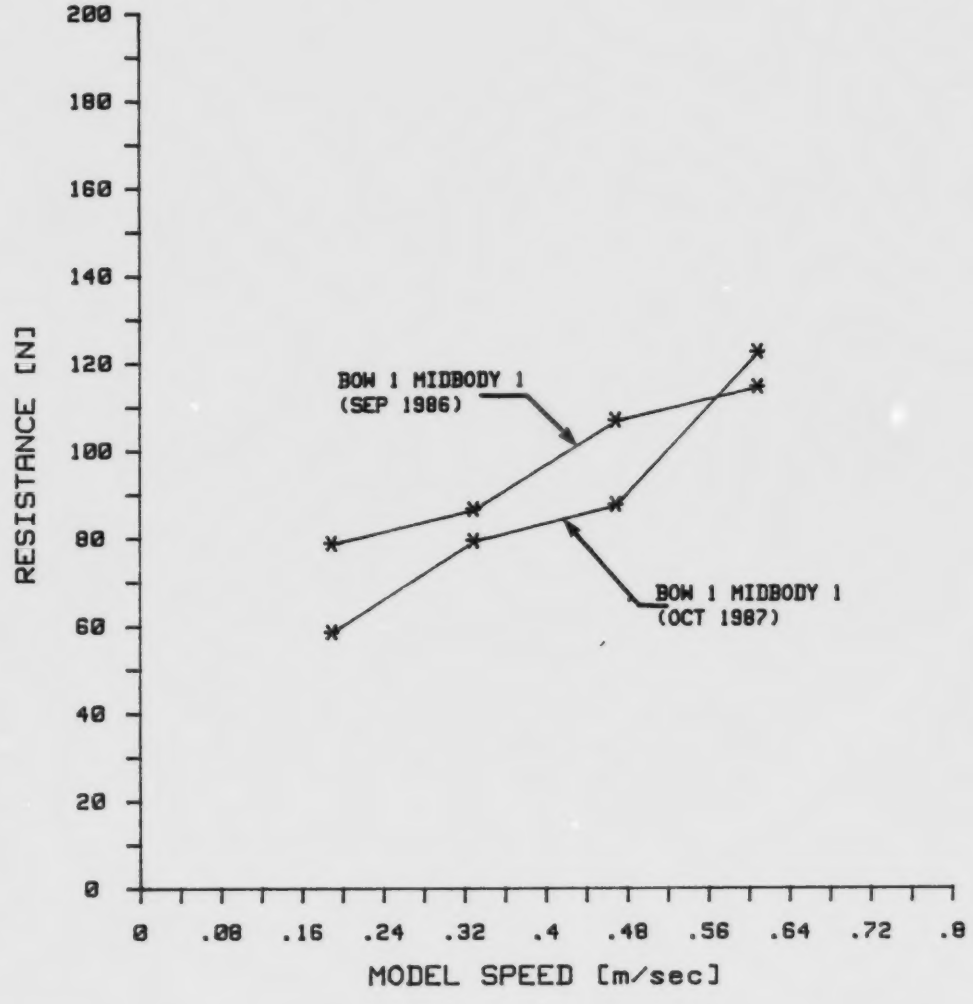
c) Data analysis; The analysis of resistance data as a function of friction coefficient

4.3.1 Data Overview

A review of Table 4.1 shows that the target ice strength and ice thicknesses were achieved with a high level of consistency. The ice crushing and shear strengths were not measured to any great extent and this is normal for current model testing. However, variations in the ice crushing and shear strength are increasingly being studied as a possible source of the variations in both different model test facilities and test repetitions at the same tank.

FIGURE 4.1

COMPARISON OF TWO IDENTICAL TESTS FROM THE FRICTION PROGRAM AT IMD



Target strength = 19 kPa
Target thickness = 50 mm
Friction coef. = 0.061

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TABLE 4.1

IMD FRICTION PROGRAM
UNCORRECTED TEST RESULTS

TEST #	ICE THICK [mm]	FLEXURAL STRENGTH [kPa]	SPEED [m/s]	RESISTANCE OR THRUST [N]	NON-DIM VALUE OR CORR.	TEST DESCRIPTION	NOTE
1	49.0	19.0	.190	76.0	0.000	1BOW 1 MIDBODY 1	
2	51.0	19.0	.330	89.0	0.000	1BOW 1 MIDBODY 1	
2	49.0	19.0	.470	103.0	0.000	1BOW 1 MIDBODY 1	
2	49.0	19.0	.610	111.0	0.000	1BOW 1 MIDBODY 1	
3	39.0	17.0	.190	50.0	0.000	TBOW 1 MIDBODY 1	
3	41.0	17.0	.320	63.0	0.000	TBOW 1 MIDBODY 1	
3	40.0	17.0	.460	70.0	0.000	TBOW 1 MIDBODY 1	
3	40.0	17.0	.600	81.0	0.000	TBOW 1 MIDBODY 1	
3	39.0	0.0	.190	20.5	0.000	TBOW 1 MIDBODY 1	
3	41.0	0.0	.320	37.0	0.000	TBOW 1 MIDBODY 1	
3	40.0	0.0	.460	41.0	0.000	TBOW 1 MIDBODY 1	
3	40.0	0.0	.600	43.0	0.000	TBOW 1 MIDBODY 1	
4	49.0	19.0	.180	46.0	0.000	BOW 2 MIDBODY 1	
4	50.0	19.0	.320	59.0	0.000	BOW 2 MIDBODY 1	
4	50.0	19.0	.460	76.0	0.000	BOW 2 MIDBODY 1	
4	50.0	19.0	.600	88.0	0.000	BOW 2 MIDBODY 1	
4	50.0	0.0	.190	20.0	0.000	BOW 2 MIDBODY 1	
4	50.0	0.0	.320	24.0	0.000	BOW 2 MIDBODY 1	
4	50.0	0.0	.600	36.0	0.000	BOW 2 MIDBODY 1	
5	48.0	16.0	.190	56.0	0.000	BOW 3 MIDBODY 1	
5	49.0	16.0	.330	74.0	0.000	BOW 3 MIDBODY 1	
5	49.0	16.0	.470	86.0	0.000	BOW 3 MIDBODY 1	
5	49.0	16.0	.600	103.0	0.000	BOW 3 MIDBODY 1	
5	49.0	0.0	.330	34.0	0.000	BOW 3 MIDBODY 1	
5	49.0	0.0	.600	53.0	0.000	BOW 3 MIDBODY 1	
6	48.0	19.0	.190	39.0	0.000	BOW 2 MIDBODY 2	
6	48.0	19.0	.330	45.0	0.000	BOW 2 MIDBODY 2	
6	48.0	19.0	.470	57.0	0.000	BOW 2 MIDBODY 2	
6	48.0	19.0	.600	60.0	0.000	BOW 2 MIDBODY 2	
6	48.0	0.0	.190	15.0	0.000	BOW 2 MIDBODY 2	
6	48.0	0.0	.330	21.0	0.000	BOW 2 MIDBODY 2	
6	48.0	0.0	.470	25.0	0.000	BOW 2 MIDBODY 2	
6	48.0	0.0	.600	31.0	0.000	BOW 2 MIDBODY 2	
7	48.0	17.0	.190	66.0	0.000	BOW 3 MIDBODY 2	
7	50.0	17.0	.330	78.0	0.000	BOW 3 MIDBODY 2	

= Data corrected with alternative zero strength data
from the same test set, at the defined speed
% = Data corrected with test defined by the number
preceeding %, followed by test speed
Target thicknesses = 30 and 40 mm
Target strength = 19 kPa

TABLE 4.1 CON'T

IMD FRICTION PROGRAM
UNCORRECTED TEST RESULTS

TEST #	ICE THICK [mm]	FLEXURAL STRENGTH [kPa]	SPEED [m/s]	RESISTANCE OR THRUST [N]	NON-DIM VALUE OR CORR.	TEST DESCRIPTION	NOTE
7	49.0	17.0	.470	92.0	0.000	BOW 3 MIDBODY 2	
7	50.0	17.0	.600	101.0	0.000	BOW 3 MIDBODY 2	
7	48.0	0.0	.190	29.0	0.000	BOW 3 MIDBODY 2	
7	50.0	0.0	.330	37.0	0.000	BOW 3 MIDBODY 2	
7	49.0	0.0	.470	46.0	0.000	BOW 3 MIDBODY 2	
7	50.0	0.0	.600	55.0	0.000	BOW 3 MIDBODY 2	
8	48.0	19.0	.190	74.0	0.000	BOW 1 MIDBODY 2	
8	50.0	19.0	.330	93.0	0.000	BOW 1 MIDBODY 2	
8	48.0	19.0	.470	98.0	0.000	BOW 1 MIDBODY 2	
8	50.0	19.0	.600	119.0	0.000	BOW 1 MIDBODY 2	
8	48.0	0.0	.190	28.0	0.000	BOW 1 MIDBODY 2	
8	50.0	0.0	.330	42.0	0.000	BOW 1 MIDBODY 2	
8	48.0	0.0	.470	48.0	0.000	BOW 1 MIDBODY 2	
8	50.0	0.0	.600	58.0	0.000	BOW 1 MIDBODY 2	
9	48.0	23.0	.190	65.0	0.000	BOW 3 MIDBODY 3	
9	50.0	23.0	.330	86.0	0.000	BOW 3 MIDBODY 3	
9	49.0	23.0	.470	97.0	0.000	BOW 3 MIDBODY 3	
9	50.0	23.0	.600	124.0	0.000	BOW 3 MIDBODY 3	
9	48.0	0.0	.190	26.0	0.000	BOW 3 MIDBODY 3	
9	50.0	0.0	.330	38.0	0.000	BOW 3 MIDBODY 3	
9	49.0	0.0	.470	45.0	0.000	BOW 3 MIDBODY 3	
9	50.0	0.0	.600	51.0	0.000	BOW 3 MIDBODY 3	
10	51.0	18.0	.190	51.0	0.000	BOW 2 MIDBODY 3	
10	54.0	18.0	.330	65.0	0.000	BOW 2 MIDBODY 3	
10	52.0	18.0	.470	78.0	0.000	BOW 2 MIDBODY 3	
10	53.0	18.0	.600	89.0	0.000	BOW 2 MIDBODY 3	
10	51.0	0.0	.190	23.0	0.000	BOW 2 MIDBODY 3	
10	54.0	0.0	.330	31.0	0.000	BOW 2 MIDBODY 3	
10	52.0	0.0	.470	40.0	0.000	BOW 2 MIDBODY 3	
10	53.0	0.0	.600	43.0	0.000	BOW 2 MIDBODY 3	
11	46.0	21.0	.190	77.0	0.000	BOW 1 MIDBODY 3	
11	48.0	21.0	.330	84.0	0.000	BOW 1 MIDBODY 3	
11	47.0	21.0	.600	109.0	0.000	BOW 1 MIDBODY 3	
11	46.0	0.0	.190	28.0	0.000	BOW 1 MIDBODY 3	

‡ = Data corrected with alternative zero strength data
from the same test set, at the defined speed
% = Data corrected with test defined by the number
preceeding %, followed by test speed
Target thicknesses = 50 and 40 mm
Target strength = 19 kPa

TABLE 4.1 CON'T

IMD FRICTION PROGRAM
UNCORRECTED TEST RESULTS

TEST #	ICE THICK [mm]	FLEXURAL STRENGTH [kPa]	SPEED [m/s]	RESISTANCE OR THRUST [N]	NON-DIM VALUE OR CORR.	TEST DESCRIPTION	NOTE
11	48.0	0.0	.330	49.0	0.000	BOW 1 MIDBODY 3	
11	47.0	0.0	.600	78.0	0.000	BOW 1 MIDBODY 3	
12	49.0	20.0	.190	58.0	0.000	2BOW 1 MIDBODY 1	
12	50.0	20.0	.330	81.9	0.000	2BOW 1 MIDBODY 1	
12	48.0	20.0	.470	83.6	0.000	2BOW 1 MIDBODY 1	
12	50.0	20.0	.610	126.0	0.000	2BOW 1 MIDBODY 1	
12	49.0	0.0	.190	25.2	0.000	2BOW 1 MIDBODY 1	
12	50.0	0.0	.330	28.5	0.000	2BOW 1 MIDBODY 1	
12	48.0	0.0	.470	41.3	0.000	2BOW 1 MIDBODY 1	
12	50.0	0.0	.610	52.5	0.000	2BOW 1 MIDBODY 1	
13	47.0	20.0	.190	114.6	0.000	BOW 4 MIDBODY 1	
13	49.0	20.0	.330	122.9	0.000	BOW 4 MIDBODY 1	
13	49.0	20.0	.470	148.7	0.000	BOW 4 MIDBODY 1	
13	50.0	20.0	.610	198.3	0.000	BOW 4 MIDBODY 1	
13	47.0	0.0	.190	49.9	0.000	BOW 4 MIDBODY 1	
13	49.0	0.0	.330	70.9	0.000	BOW 4 MIDBODY 1	
13	49.0	0.0	.470	76.6	0.000	BOW 4 MIDBODY 1	
13	50.0	0.0	.610	96.4	0.000	BOW 4 MIDBODY 1	

= Data corrected with alternative zero strength data
from the same test set, at the defined speed
% = Data corrected with test defined by the number
preceeding %, followed by test speed
Target thicknesses = 50 and 40 mm
Target strength = 19 kPa

This can be demonstrated by considering the test repeated by IMD for this programme. Figure 4.1 shows the results from two ice sheets, one conducted in September 1986 (1Bow1Midbody1) and the second in October 1987 (2Bow1Midbody1) using an identical model of the ARCTIC. It can be seen from Table 4.1 that the target ice thickness and strength was the same for both ice sheets and a review of the measured values of ice ice strength and thickness show that these were reproduced well during the model test. However it can be seen from the results, which have been corrected using the procedure discussed in the next subsection, that the repeated test showed very good agreement for one speed (0.61 m/sec) but less consistent results for the remaining speeds. In summary the variations between the two resistance values were;

Speed = 0.19 m/sec Variance = 34.8 %
Speed = 0.33 m/sec Variance = 9.1 %
Speed = 0.47 m/sec Variance = 22.1 %
Speed = 0.61 m/sec Variance = 6.5 %

It is interesting to note that the difference between the two sets of data may be considered as an initial, zero speed difference and a slightly different speed dependence. The test run with the lower resistance was the test conducted in October 1987. The higher resistance test was conducted a year earlier in September 1986.

In addition to considering the level ice data the two ice sheets may be compared based on the presawn tests. Unfortunately presawn tests were not conducted for the September 1986 tests, however, presawn tests were conducted on the remaining tests in 1986. A later section in this report will demonstrate that the middle and first rough surface are very similar, and this permits the comparison shown in Figure 4.2. Comparing this result with Figure 4.1 it can be seen that the presawn tests correlate considerably better than the level ice tests. This may be due to a number of reasons but is thought to be associated with variations in the mechanical properties of the level ice that cannot be identified from the conventional testing methods.

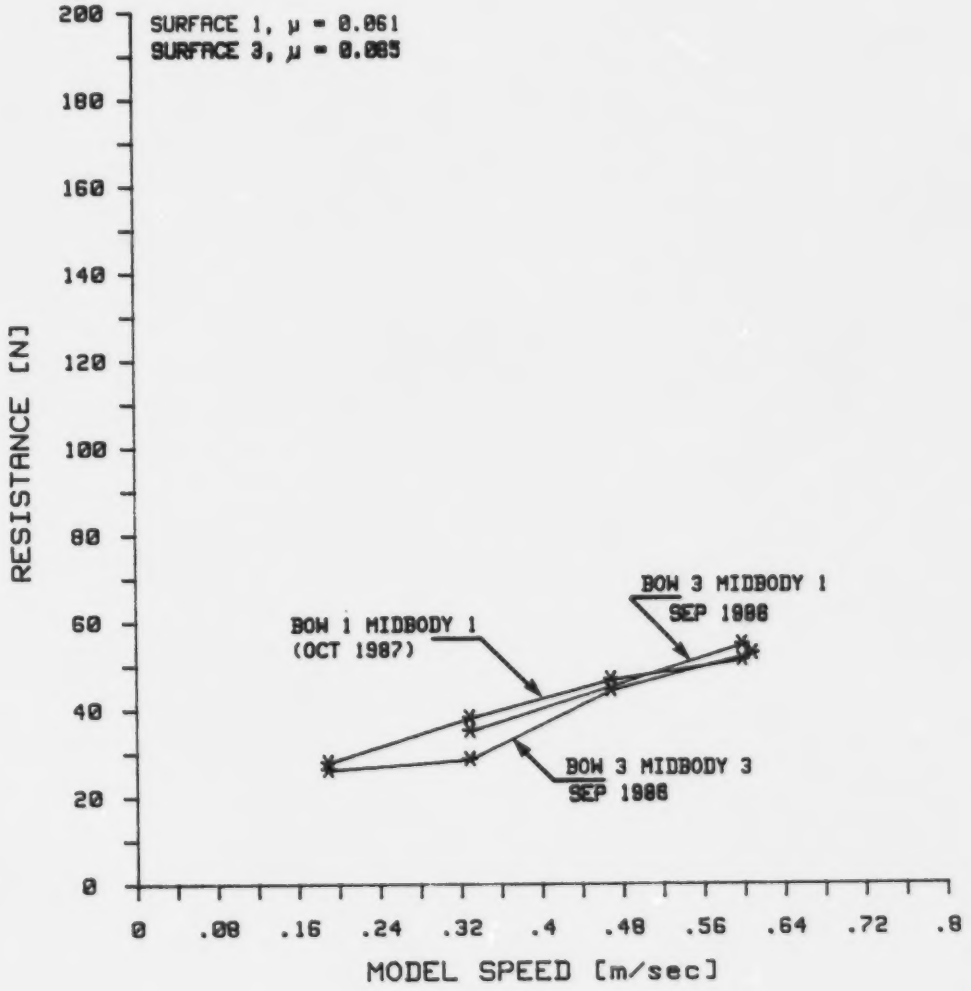
These two tests may also be reviewed by dividing the level ice resistance with a variable group of strength and thickness. This is shown in Figure 4.3 for three tests using the same model.

The three tests shown in Figure 4.3 are the two tests with the same ice thickness discussed above in Figure 4.1 and an additional test that was conducted as part of the September 1986 tests with a thinner ice sheet. The exponents of ice strength and thickness are shown on the figure and discussed in the next section. The results of this normalisation is that the two tests conducted in 1986 agree extremely well and could not demonstrate any better correlation. However, the later test in 1987 is again inconsistent with the other tests and further supports the theory that the variation in the tests is due to varying ice mechanical properties.

Considering the discrepancies, discussed above, with the ice sheet tested in October 1987, all the subsequent data analysis is conducted with the middle friction coefficient tested in September 1986. The exception to

FIGURE 4.2

COMPARISON BETWEEN SEPTEMBER 1986 AND OCTOBER 1987 PRE SAWN TESTS



Target strength = 19 kPa
Target thickness = 50 mm
Friction coef. = 0.061 and 0.065

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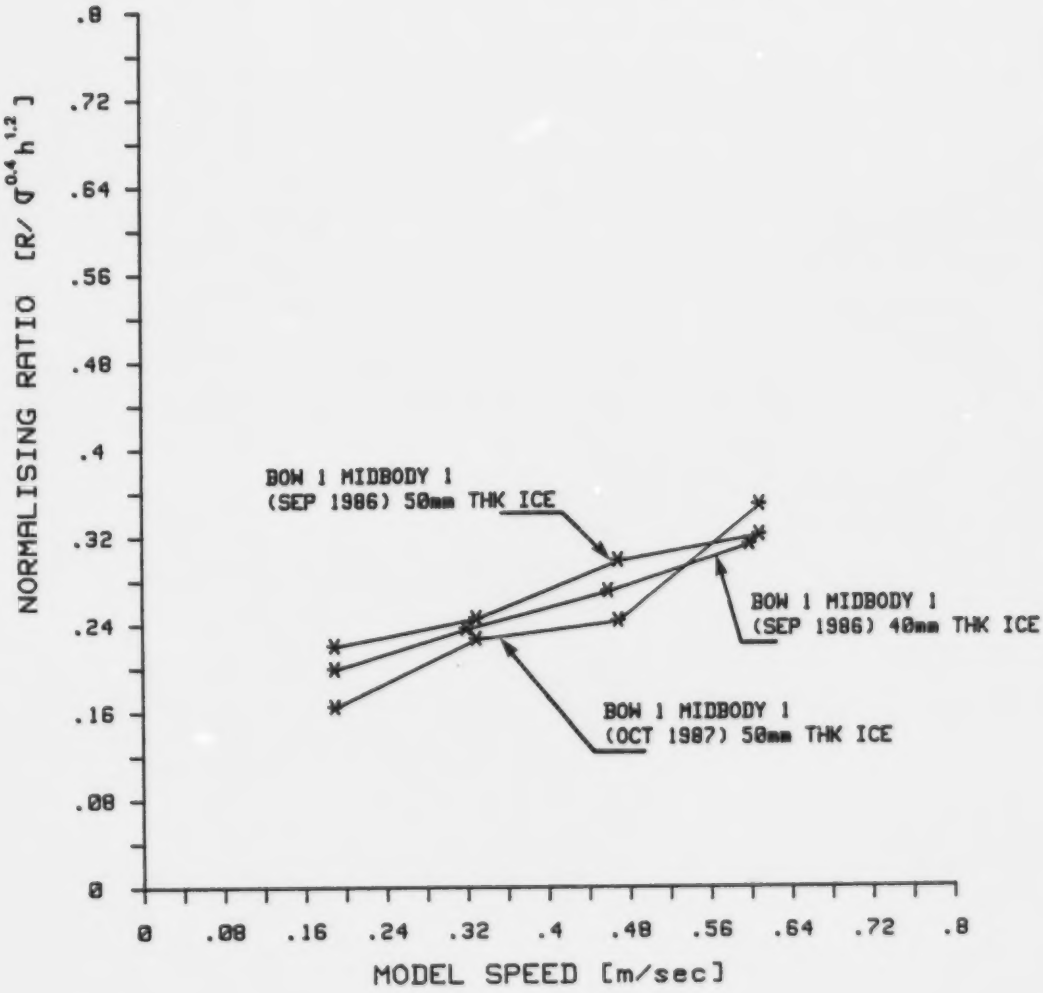
FIGURE 4.3

TEST RESULTS FROM IMD FRICTION PROGRAM
ANALYSIS OF TESTS REPEATED WITH THE SAME MODEL



Target ice strength = 19 kPa
Target ice thickness = 40mm and 50mm
friction coef. = 0.061

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this is the comparison with the rough surface, which was tested in October 1987 at the same time as the second test with the middle friction coefficient.

In addition to reviewing identical model test runs the data may also be assessed on a more general basis by considering the consistency of the data plots of resistance as a function of speed. This has been done for three example tests in Figure 4.4.

The figure shows the results of three tests, the base case friction coefficient of 0.061 on the bow and midbody, the midbody replaced with the smooth surface, 0.004, and the bow and midbody replaced with the smooth surface. It can be seen from the figure that the tests are consistent with each other and with speed. This type of output is representative of the high quality data that was obtained during the tests in Europe with the ARCTIC in 1983/84.

4.3.2 Data Correction

The model tests were all conducted with target ice thicknesses and strengths, however, as with any physical testing, the target values were not always obtained. As a result some minor adjustments or nomalisations are necessary to ensure that when the data is analysed for variations in friction coefficient the comparison is independent of ice thickness and strength considerations.

There are a number of methods that may be used to normalise the data and these may be summarised as;

1. Thickness and ice strength corrected as a function of a variable group in the form.

$$R_c = R_m * \{(h_t^a \times o_t^b) / (h_m^a \times o_m^b)\}$$

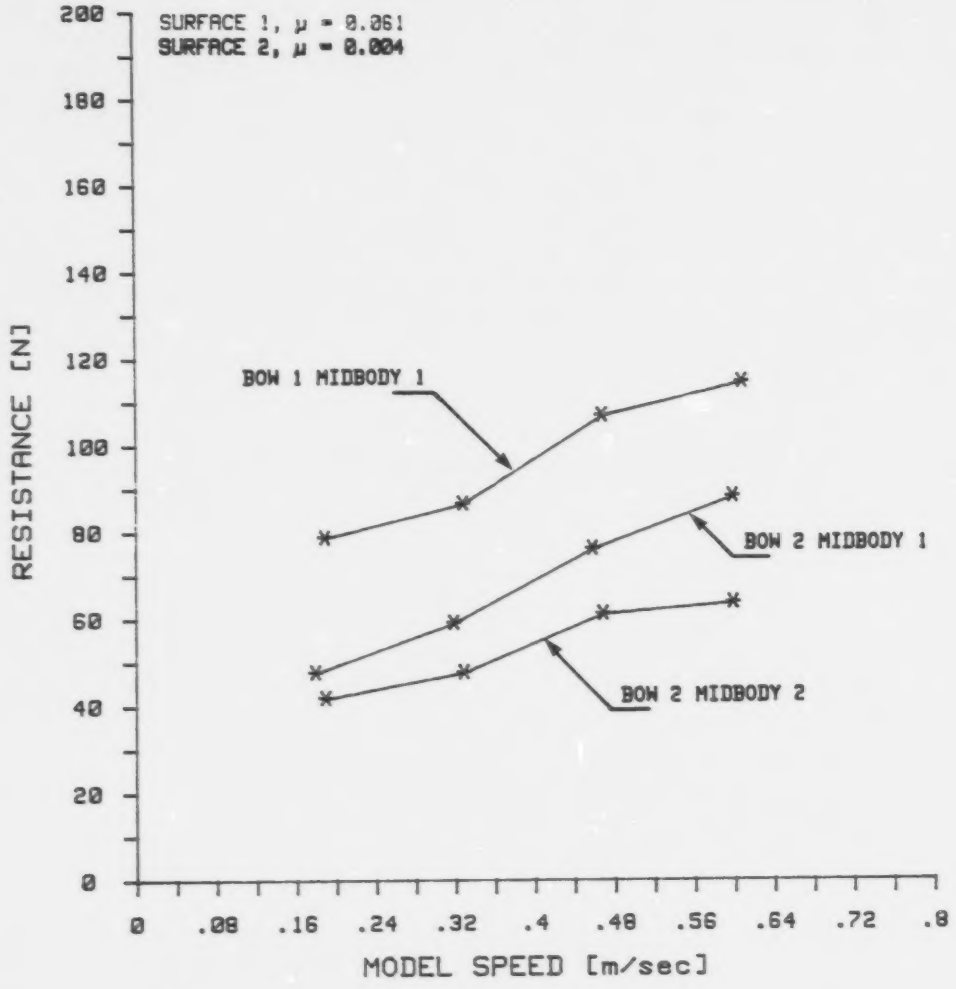
R_m = Measured Resistance
R_c = Corrected Resistance
h_m = Measured Thickness
h_t = Target Thickness
o_m = Measured Strength
o_t = Target Strength
a, b = Empirical Indices, normally between one and two.

2. Based on tests with the same model in different ice thicknesses, an extrapolation or interpolation to the target thickness based on a constant ratio of rate of change of resistance with ice thickness over measured resistance at a specific speed.

3. Based on presawn or zero strength ice tests, an extrapolation or interpolation to the target ice strength based on a constant ratio of rate of change of resistance with ice strength over measured resistance at a specific speed.

FIGURE 4.4

COMPARISON BETWEEN THREE EXAMPLE TEST RUNS FROM IMD PROGRAM



Target strength = 19 kPa
Target thickness = 50 mm
Friction coef. = 0.061 and 0.004

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Any one, or a combination of these correction methods may be used and are discussed in the following text.

The correction to target ice thickness and strength using the variable group of thickness and strength is based on the assumption that the resistance conforms in a consistant way to these variables, raised to a selected index, independant of bow form. Work associated with this type of analysis has shown that this is not always the case. For example, Figure 4.5 presents the results from the model tests of the Melville Bow on the ARCTIC in HSVA, West Germany.

The model test data is presented in a normalised form with the strength index equal to 0.4 and the thickness index equal to 1.2. It can be seen that this results in a consistant relationship between this variable group and speed. It should be noted that for these tests the strength variation was very small and, for these tests, the relationship is almost independent of the strength index. However considering tests conducted in WARC for the same model under varying strength conditions the 0.4 index for strength appears to normalise the data well. This is shown in Figure 4.6 for the original and Melville bow forms.

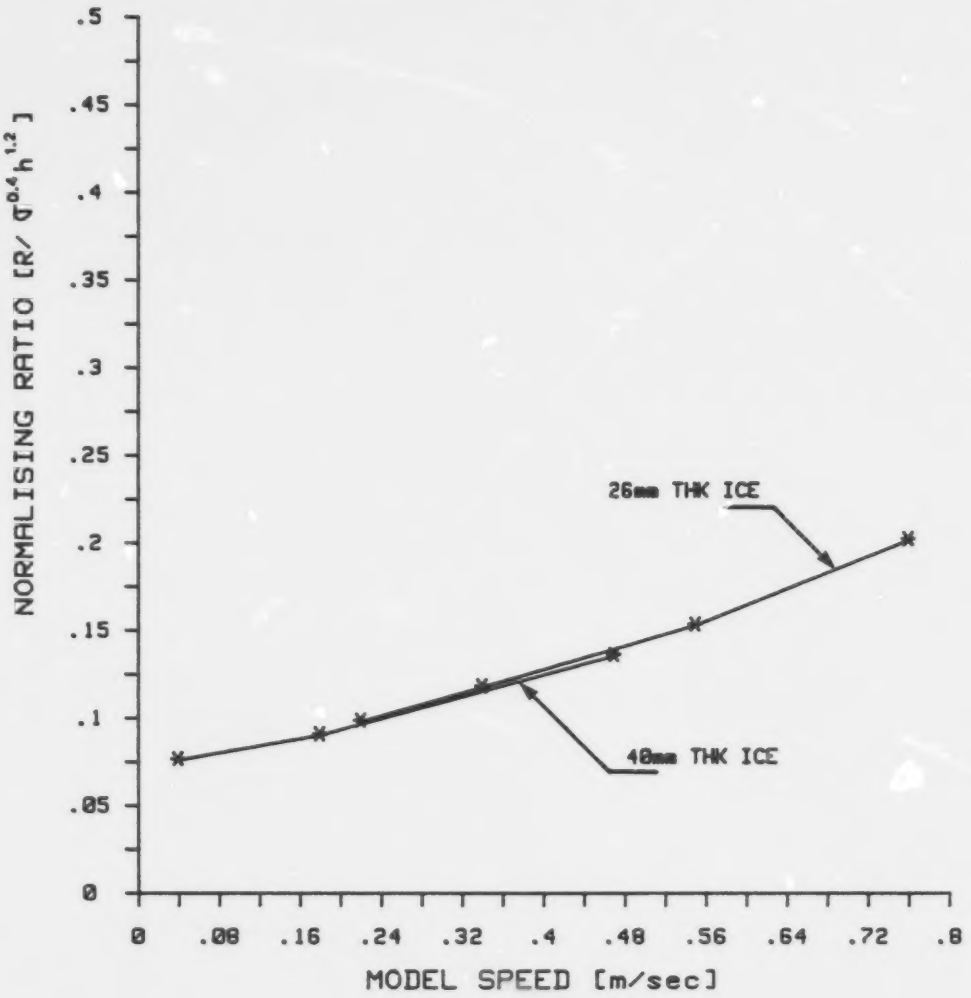
Figure 4.7 shows the data from the original bow in HSVA for two different thickesses. When this figure is compared with Figure 4.5 it can be seen that for the original bow the variable group is more consistant for different thicknesses when the ice thickness index is two. This result may lead to the conclusion that the thickness and strength index is bow form dependent.

This may be considered with regard to the data collected from the IMD tests as shown in Figure 4.8. This figure shows the results from the Melville bow tests at two ice thicknesses with a thickness index of 1.2 and a strength index of 0.4. Unfortunately since the original ARCTIC bow has not yet been tested at IMD, the similar test result for that bow cannot be reviewed. However Figure 4.8 does indicate that the IMD data tends to conform in the same way as the WARC and HSVA data sets.

The alternative method for correcting the results from the ice sheets is to use tests of the model in a different ice thickness for the thickness correction and the results of the presawn tests for the strength correction. This procedure is described in detail in the Appendix 3 but may be summarised as follows. The correction to resistance for variations in thickness is calculated by assuming a linear relationship between the resistance and thickness for a specific speed. The resistance at the target ice thickness is simply interpolated between the two values of resistance at different ice thicknesses. When data exists this is done independently at each speed, if data at all the speeds does not exist then a constant relative rate of change of resistance with ice thickness is calculated for the closest speed and used instead. It should be noted that the correction method discussed and used in the model test report from IMD, Appendix 3 uses an average relative rate of change of resistance with thickness for all the data.

FIGURE 4.5

MODEL TEST RESULTS FROM HSVA
NORMALISED DATA FOR THE MELVILLE BOW



Target ice strength = 19 kPa
Target ice thickness = 26mm and 40mm

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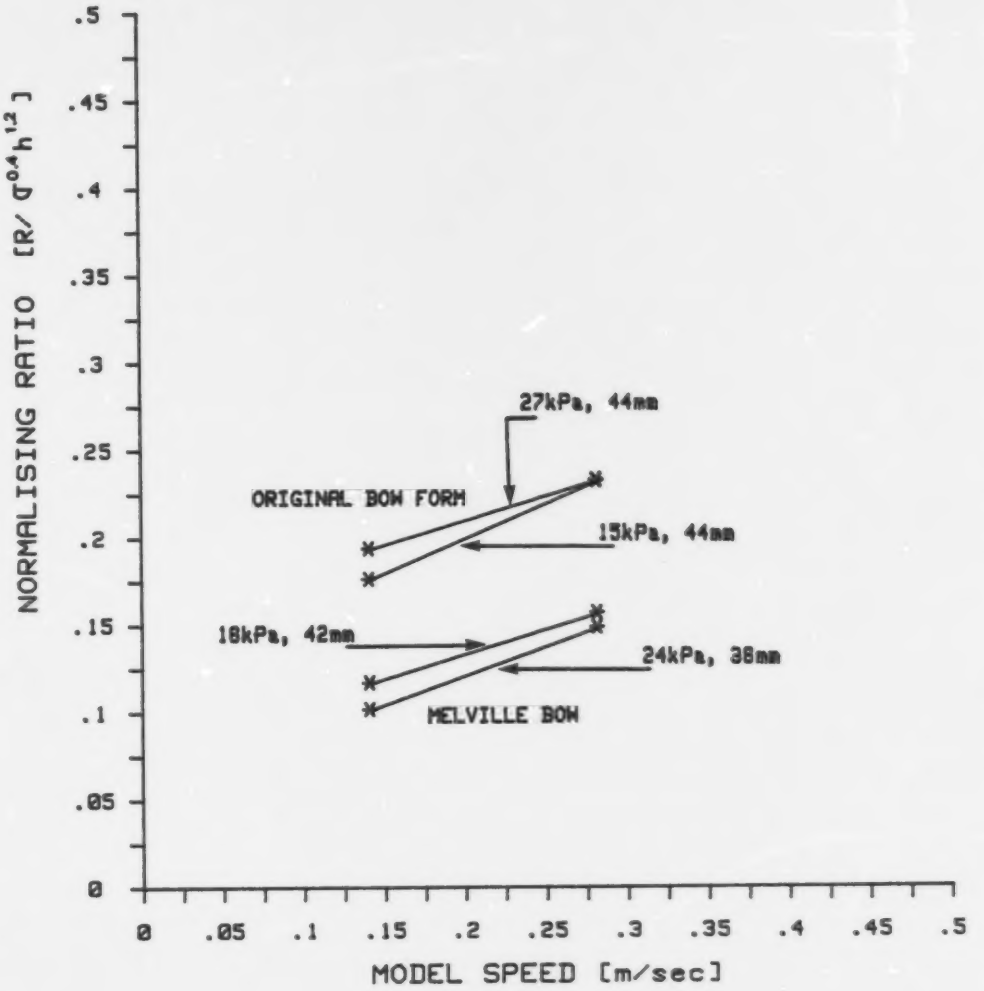
FIGURE 4.6

MODEL TEST RESULTS FROM WARC NORMALISED DATA FOR THE ORIGINAL AND MELVILLE BOWS



Ice strength = 15 kPa to 27 kPa
Ice thickness = 36mm to 44mm

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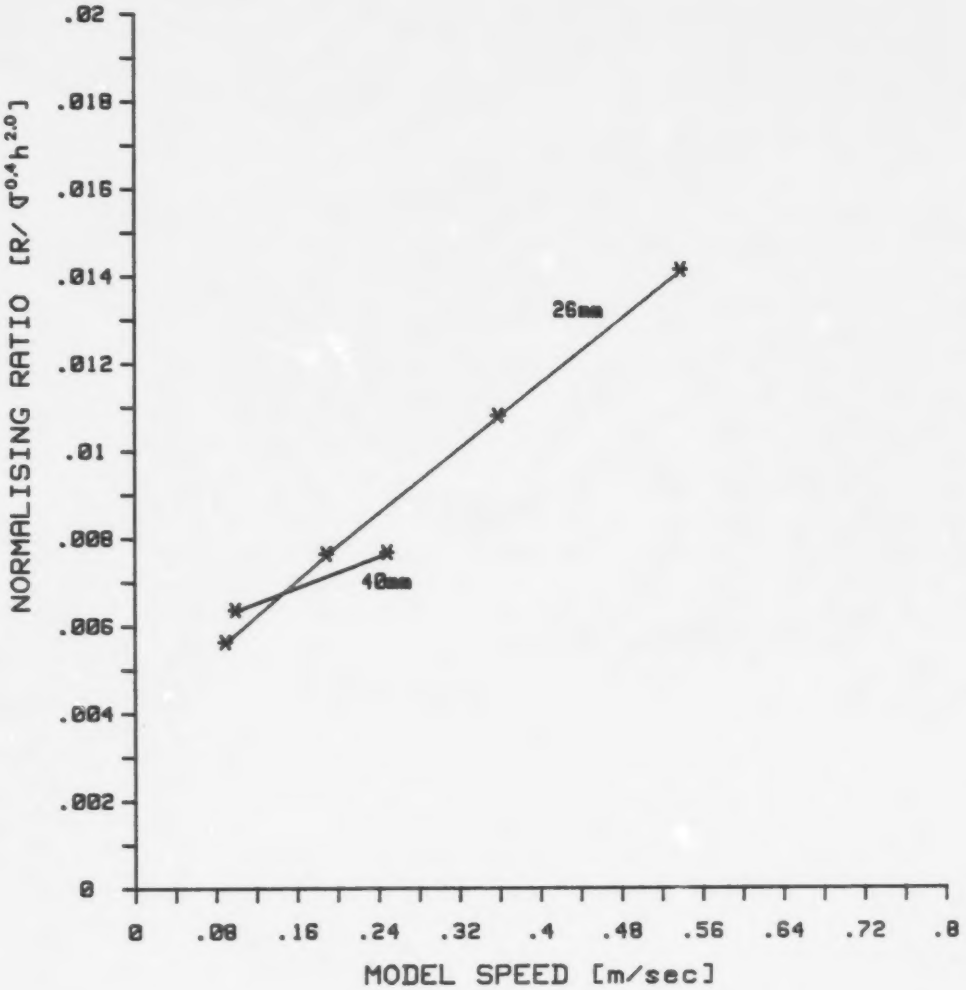
FIGURE 4.7

MODEL TEST RESULTS FROM HSVA
ARCTIC WITH ORIGINAL BOW



Target ice strength = 19 kPa
Target ice thickness = 26mm and 40mm

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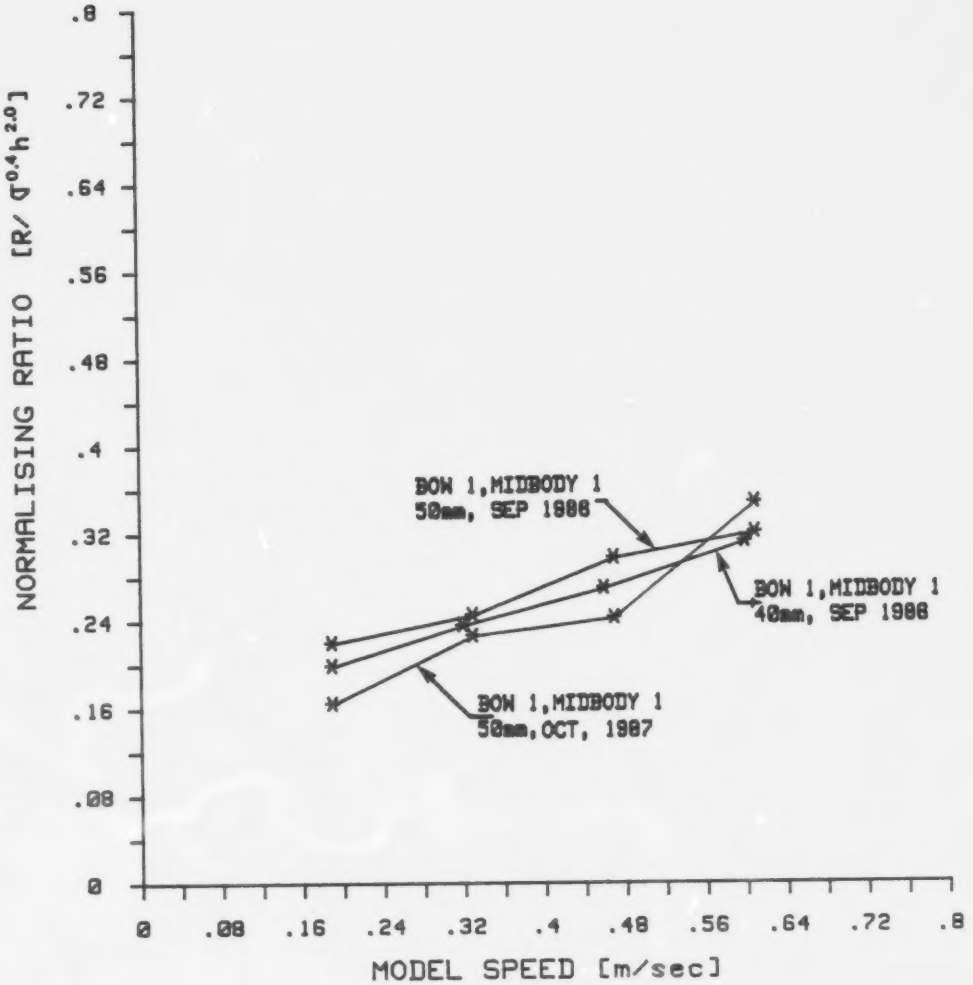
FIGURE 4.8

NORMALISED DATA FROM IMD FRICTION PROGRAM



Target ice strength = 19 kPa
Target ice thickness = 40mm and 50mm
Friction coef. = 0.061

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The correction to resistance for variations in strength is calculated from the zero strength or presawn ice sheets. The resistance of the model in the presawn test is assumed to correspond to zero flexural strength. Using this value and the measured value during the normal level ice test at the same speed test, the resistance at the target ice strength is calculated by interpolation, or extrapolation. In the event that an identical speed was not run in the presawn then the relative change in resistance as a function of strength is calculated from the closest speed and used in lieu. Figure 4.1 presents the comparison of the two identical model tests conducted in September 1986 and October 1987 using this method. The result of correcting the data in this way can be seen to be similar to the alternative methods.

In this example, normalising to the resistance for thickness and strength have been calculated separately based on the measured resistance. The alternative to this approach is to apply the second correction to normalised resistance values. This approach was considered, but, when the results from the two similar ice sheets were compared they produced a less consistent result than correcting the data separately, independently of which normalisation was applied first. As a result all subsequent corrections to resistance are calculated from the accumulated values from each method, based on the measured resistance.

The validity of these procedures, to normalise the resistance for variations in strength and thickness, may be assessed by comparing the two identical tests conducted on the ARCTIC model with a friction coefficient of 0.06. Table 4.2 is a comparison between the normalised resistances of the two identical tests using a number of different methods to correct the measured data to target values. The first three columns of the table present the raw uncorrected data at the four test speeds, for test 1 (September 1986) and test two (October 1987). The next two sets of three columns present the resultant corrected data from two variable group connections. The first two columns of each set are the corrected resistances and the third column is the percentage difference between the two tests. The fourth set of three columns presents the same data for the correction technique using presawn ice tests and/or other ice sheets to develop resistance versus ice strength and resistance versus ice thickness relationships. Based on the comparison between the two identical model tests, the normalisation based on using an ice sheet of a different thickness and the presawn tests appear to result in the closest correlation, however, it may be noted that the variable group of thickness to the power 1.2 and strength to the power 0.4 results in a very similar level of correlation.

Based on this result it was elected to normalise all the data using the results from the two ice sheets with different thicknesses for the thickness correction and the presawn tests for the strength correction. The data used in the subsequent analysis is presented in Table 4.3 at target strength and thickness values.

TABLE 4.2

COMPARISON OF CORRECTED RESISTANCE DATA USING THREE DIFFERENT METHODS

Raw model test data			Variable Group $R/\sigma^{0.4} \cdot h^{1.2}$			Variable Group $\sigma \cdot h^2$			Data Corrected with Additional Ice Sheets		
Speed (m/sec)	Resistance (N)		Corrected Resistance (N)		Percentage Difference	Corrected Resistance (N)		Percentage Difference	Corrected Resistance (N)		Percentage Difference
	Test 1	Test 2	Test 1	Test 2		Test 1	Test 2		Test 1	Test 2	
0.19	76	58	77.9	58.2	34.0	79.1	57.4	37.8	79	58	34.8
0.33	89	82	86.9	80.2	8.4	85.5	77.8	9.9	86	80	9.1
0.47	103	84	105.5	86.0	22.7	107.2	86.2	24.4	107	87	22.1
0.61	111	126	113.7	123.4	7.9	115.6	119.7	3.4	114	122	-6.5

4.3.3 Data Analysis

The variation of resistance with friction coefficient has been analysed by comparing each combination of friction coefficient with the middle coefficient on the bow and mid body. To reaffirm the values of friction coefficient associated with each surface;

Surface 1; Friction Coefficient = 0.061 ; Middle roughness CLA = 1.257 μm

Surface 2; Friction Coefficient = 0.004 ; Smooth surface CLA = 0.416 μm

Surface 3; Friction Coefficient = 0.065 ; First rough surface CLA = 1.236 μm

Surface 4; Friction Coefficient = 0.354 ; Second rough surface

It may be noted again that the original rough surface tested in the first series of tests was not considered to be sufficiently rougher than the middle surface and resulted in additional testing.

a) Middle roughness compared with the first rough surface

1. It can be seen from the friction coefficient and CLA values noted above that the first rough surface is not significantly different from the middle surface. This is further confirmed by a review of the resistance data from the ice sheets. Figure 4.9 shows the data collected from all the combinations using the middle roughness, surface 1, and the first rough surface, surface 3. It can be seen from this data that the scatter of results is not large and may be considered to be generally within the bounds of experimental accuracy.

TABLE 4.3

FRICTION PROGRAM
DATA CORRECTED TO TARGET
THICKNESS AND STRENGTH

TEST #	ICE THICK [mm]	FLEXURAL STRENGTH [kPa]	SPEED [m/s]	RESISTANCE OR THRUST [N]	NON-DIM VALUE OR CORR.	TEST DESCRIPTION	NOTE
1	49.0	19.0	.190	78.6	2.600	1BOW 1 MIDBODY 1	
1	51.0	19.0	.330	86.4	-2.600	1BOW 1 MIDBODY 1	
1	49.0	19.0	.470	106.7	3.667	1BOW 1 MIDBODY 1	
1	49.0	19.0	.610	114.3	3.333	1BOW 1 MIDBODY 1	
2	39.0	17.0	.190	56.1	6.071	TBOW 1 MIDBODY 1	
2	41.0	17.0	.320	63.5	.459	TBOW 1 MIDBODY 1	
2	40.0	17.0	.460	73.4	3.412	TBOW 1 MIDBODY 1	
2	40.0	17.0	.600	85.5	4.471	TBOW 1 MIDBODY 1	
2	39.0	0.0	.190	20.5	0.000	TBOW 1 MIDBODY 1	
2	41.0	0.0	.320	37.0	0.000	TBOW 1 MIDBODY 1	
2	40.0	0.0	.460	41.0	0.000	TBOW 1 MIDBODY 1	
2	40.0	0.0	.600	43.0	0.000	TBOW 1 MIDBODY 1	
3	49.0	19.0	.180	47.6	1.574	BOW 2 MIDBODY 1	
3	50.0	19.0	.320	59.0	0.000	BOW 2 MIDBODY 1	
3	50.0	19.0	.460	76.0	0.000	BOW 2 MIDBODY 1	
3	50.0	19.0	.600	88.0	0.000	BOW 2 MIDBODY 1	
3	50.0	0.0	.190	20.0	0.000	BOW 2 MIDBODY 1	
3	50.0	0.0	.320	24.0	0.000	BOW 2 MIDBODY 1	
3	50.0	0.0	.600	36.0	0.000	BOW 2 MIDBODY 1	
4	48.0	16.0	.190	65.5	9.507	BOW 3 MIDBODY 1	#.33
4	49.0	16.0	.330	83.7	9.662	BOW 3 MIDBODY 1	
4	49.0	16.0	.470	97.8	11.778	BOW 3 MIDBODY 1	#.33
4	49.0	16.0	.600	115.5	12.468	BOW 3 MIDBODY 1	
4	49.0	0.0	.330	34.0	0.000	BOW 3 MIDBODY 1	
4	49.0	0.0	.600	53.0	0.000	BOW 3 MIDBODY 1	
5	48.0	19.0	.190	41.7	2.668	BOW 2 MIDBODY 2	
5	48.0	19.0	.330	47.6	2.629	BOW 2 MIDBODY 2	
5	48.0	19.0	.470	61.1	4.058	BOW 2 MIDBODY 2	
5	48.0	19.0	.600	63.6	3.604	BOW 2 MIDBODY 2	
5	48.0	0.0	.190	15.0	0.000	BOW 2 MIDBODY 2	
5	48.0	0.0	.330	21.0	0.000	BOW 2 MIDBODY 2	
5	48.0	0.0	.470	25.0	0.000	BOW 2 MIDBODY 2	
5	48.0	0.0	.600	31.0	0.000	BOW 2 MIDBODY 2	
6	48.0	17.0	.190	74.9	8.869	BOW 3 MIDBODY 2	
6	50.0	17.0	.330	82.8	4.824	BOW 3 MIDBODY 2	

= Data corrected with alternative zero strength data
from the same test set, at the defined speed
% = Data corrected with test defined by the number
preceeding %, followed by test speed
Target thicknesses = 50 and 40 mm
Target strength = 19 kPa

TABLE 4.3 CON'T

FRICTION PROGRAM
DATA CORRECTED TO TARGET
THICKNESS AND STRENGTH

TEST #	ICE THICK [mm]	FLEXURAL STRENGTH [kPa]	SPEED [m/s]	RESISTANCE OR THRUST [N]	NON-DIM VALUE OR CORR.	TEST DESCRIPTION	NOTE
5	49.0	17.0	.470	100.7	8.687	BOW 3 MIDBODY 2	
6	50.0	17.0	.600	106.4	5.412	BOW 3 MIDBODY 2	
5	48.0	0.0	.190	29.0	0.000	BOW 3 MIDBODY 2	
6	50.0	0.0	.330	37.0	0.000	BOW 3 MIDBODY 2	
5	49.0	0.0	.470	46.0	0.000	BOW 3 MIDBODY 2	
6	50.0	0.0	.600	55.0	0.000	BOW 3 MIDBODY 2	
7	48.0	19.0	.190	79.1	5.063	BOW 1 MIDBODY 2	
7	50.0	19.0	.330	93.0	0.000	BOW 1 MIDBODY 2	
7	48.0	19.0	.470	105.0	6.977	BOW 1 MIDBODY 2	
7	50.0	19.0	.600	119.0	0.000	BOW 1 MIDBODY 2	
7	48.0	0.0	.190	28.0	0.000	BOW 1 MIDBODY 2	
7	50.0	0.0	.330	42.0	0.000	BOW 1 MIDBODY 2	
7	48.0	0.0	.470	48.0	0.000	BOW 1 MIDBODY 2	
7	50.0	0.0	.600	58.0	0.000	BOW 1 MIDBODY 2	
8	48.0	23.0	.190	62.7	-2.335	BOW 3 MIDBODY 3	
8	50.0	23.0	.330	77.7	-8.348	BOW 3 MIDBODY 3	
8	49.0	23.0	.470	91.4	-5.590	BOW 3 MIDBODY 3	
8	50.0	23.0	.600	111.3	-12.696	BOW 3 MIDBODY 3	
8	48.0	0.0	.190	26.0	0.000	BOW 3 MIDBODY 3	
8	50.0	0.0	.330	38.0	0.000	BOW 3 MIDBODY 3	
8	49.0	0.0	.470	45.0	0.000	BOW 3 MIDBODY 3	
8	50.0	0.0	.600	51.0	0.000	BOW 3 MIDBODY 3	
9	51.0	18.0	.190	50.8	-.189	BOW 2 MIDBODY 3	
9	54.0	18.0	.330	59.3	-5.707	BOW 2 MIDBODY 3	
9	52.0	18.0	.470	74.6	-3.442	BOW 2 MIDBODY 3	
9	53.0	18.0	.600	83.5	-5.462	BOW 2 MIDBODY 3	
9	51.0	0.0	.190	23.0	0.000	BOW 2 MIDBODY 3	
9	54.0	0.0	.330	31.0	0.000	BOW 2 MIDBODY 3	
9	52.0	0.0	.470	40.0	0.000	BOW 2 MIDBODY 3	
9	53.0	0.0	.600	43.0	0.000	BOW 2 MIDBODY 3	
10	46.0	21.0	.190	82.9	5.870	BOW 1 MIDBODY 3	
10	48.0	21.0	.330	85.6	1.575	BOW 1 MIDBODY 3	
10	47.0	21.0	.600	115.9	6.867	BOW 1 MIDBODY 3	
10	46.0	0.0	.190	28.0	0.000	BOW 1 MIDBODY 3	

= Data corrected with alternative zero strength data
from the same test set, at the defined speed
% = Data corrected with test defined by the number
preceeding %, followed by test speed
Target thicknesses = 50 and 40 mm
Target strength = 19 kPa

TABLE 4.3 CON'T

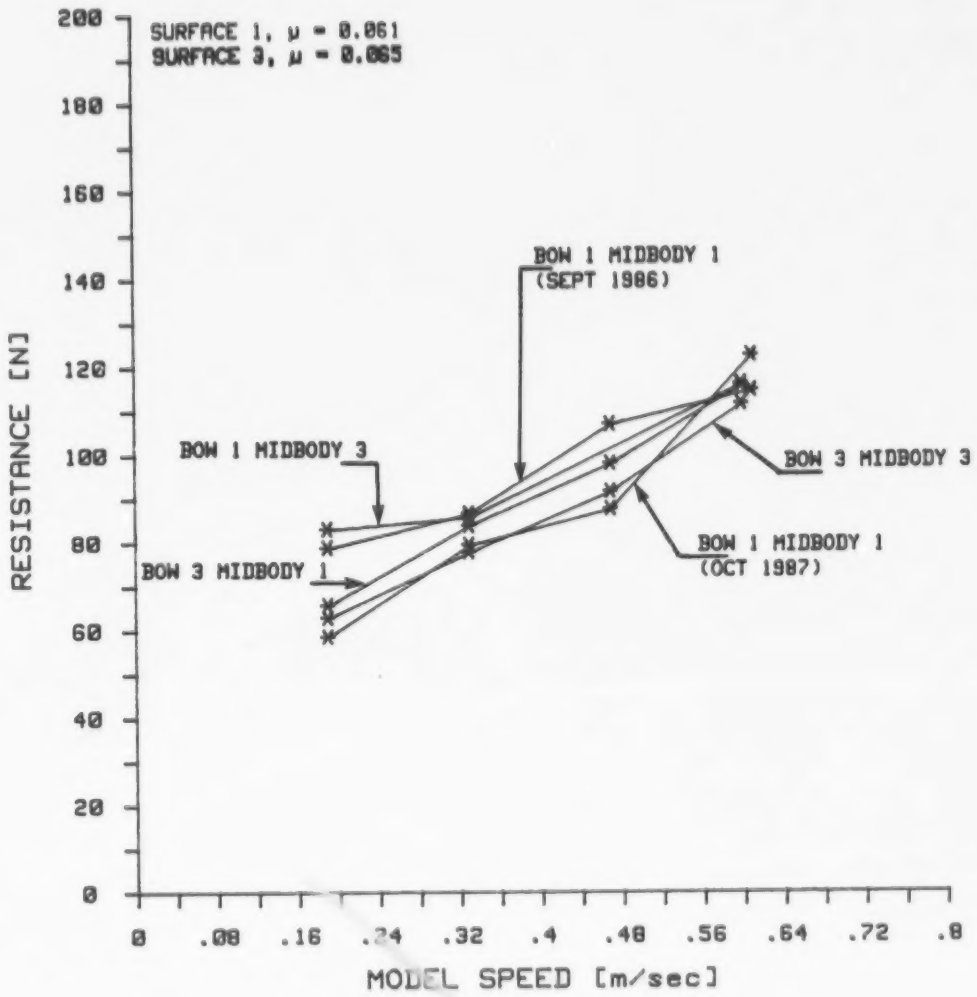
FRICTION PROGRAM
DATA CORRECTED TO TARGET
THICKNESS AND STRENGTH

TEST #	ICE THICK [mm]	FLEXURAL STRENGTH [kPa]	SPEED [m/s]	RESISTANCE OR THRUST [N]	NON-DIM VALUE OR CORR.	TEST DESCRIPTION	NOTE
10	48.0	0.0	.330	49.0	0.000	BOW 1 MIDBODY 3	
10	47.0	0.0	.600	78.0	0.000	BOW 1 MIDBODY 3	
11	49.0	20.0	.190	58.3	.344	2BOW 1 MIDBODY 1	
11	50.0	20.0	.330	79.2	-2.670	2BOW 1 MIDBODY 1	
11	48.0	20.0	.470	87.4	3.837	2BOW 1 MIDBODY 1	
11	50.0	20.0	.610	122.3	-3.675	2BOW 1 MIDBODY 1	
11	49.0	0.0	.190	25.2	0.000	2BOW 1 MIDBODY 1	
11	50.0	0.0	.330	28.5	0.000	2BOW 1 MIDBODY 1	
11	48.0	0.0	.470	41.3	0.000	2BOW 1 MIDBODY 1	
11	50.0	0.0	.610	52.5	0.000	2BOW 1 MIDBODY 1	
12	47.0	20.0	.190	123.1	8.527	BOW 4 MIDBODY 1	
12	49.0	20.0	.330	123.9	.990	BOW 4 MIDBODY 1	
12	49.0	20.0	.470	150.4	1.689	BOW 4 MIDBODY 1	
12	50.0	20.0	.610	193.2	-5.095	BOW 4 MIDBODY 1	
12	47.0	0.0	.190	49.9	0.000	BOW 4 MIDBODY 1	
12	49.0	0.0	.330	70.9	0.000	BOW 4 MIDBODY 1	
12	49.0	0.0	.470	76.6	0.000	BOW 4 MIDBODY 1	
12	50.0	0.0	.610	96.4	0.000	BOW 4 MIDBODY 1	

= Data corrected with alternative zero strength data
from the same test set, at the defined speed
% = Data corrected with test defined by the number
preceeding %, followed by test speed
Target thicknesses = 50 and 40 mm
Target strength = 19 kPa

FIGURE 4.9

IMD FRICTION PROGRAM COMPARISON BETWEEN MIDDLE AND FIRST ROUGH SURFACE



Target Strength = 19 kPa
Target Thickness = 50 mm
Friction coef. = .061 and .065

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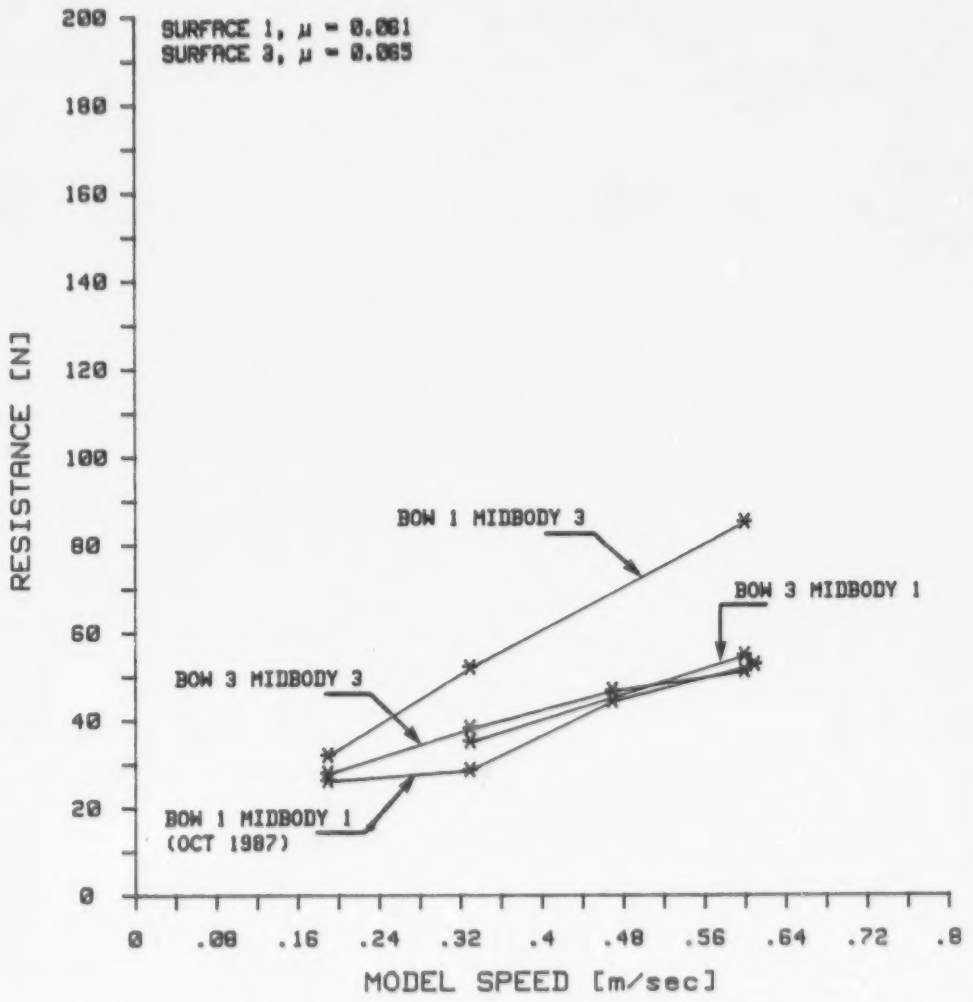
FIGURE 4.10

IMD FRICTION PROGRAM COMPARISON BETWEEN MIDDLE AND FIRST ROUGH SURFACE - PRE SAWN TESTS



Target Strength = 19 kPa
Target Thickness = 50 mm
Friction coef. = .061 and .065

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2. Figure 4.10 presents the data from the presawn tests, corrected for ice thickness, and with the exception of one data set there is no significant variation between the test results for the different friction coefficients. The variation is present in the combination of the middle bow, surface 1 and the first rough midbody, surface 3.

3. Since the combination of the first rough surface, surface 3, on the bow, is not affected and the mechanical properties of the ice do not indicate any anomalies, the reason for the high presawn resistance is unknown, but could possibly have occurred due to incorrect or misaligned cuts during the presawn ice cutting.

4. As a result of this analysis surface 1 and surface 3 have not been compared further since it is considered that any variations between them is within experimental accuracy.

b) Middle roughness compared with the smooth surface

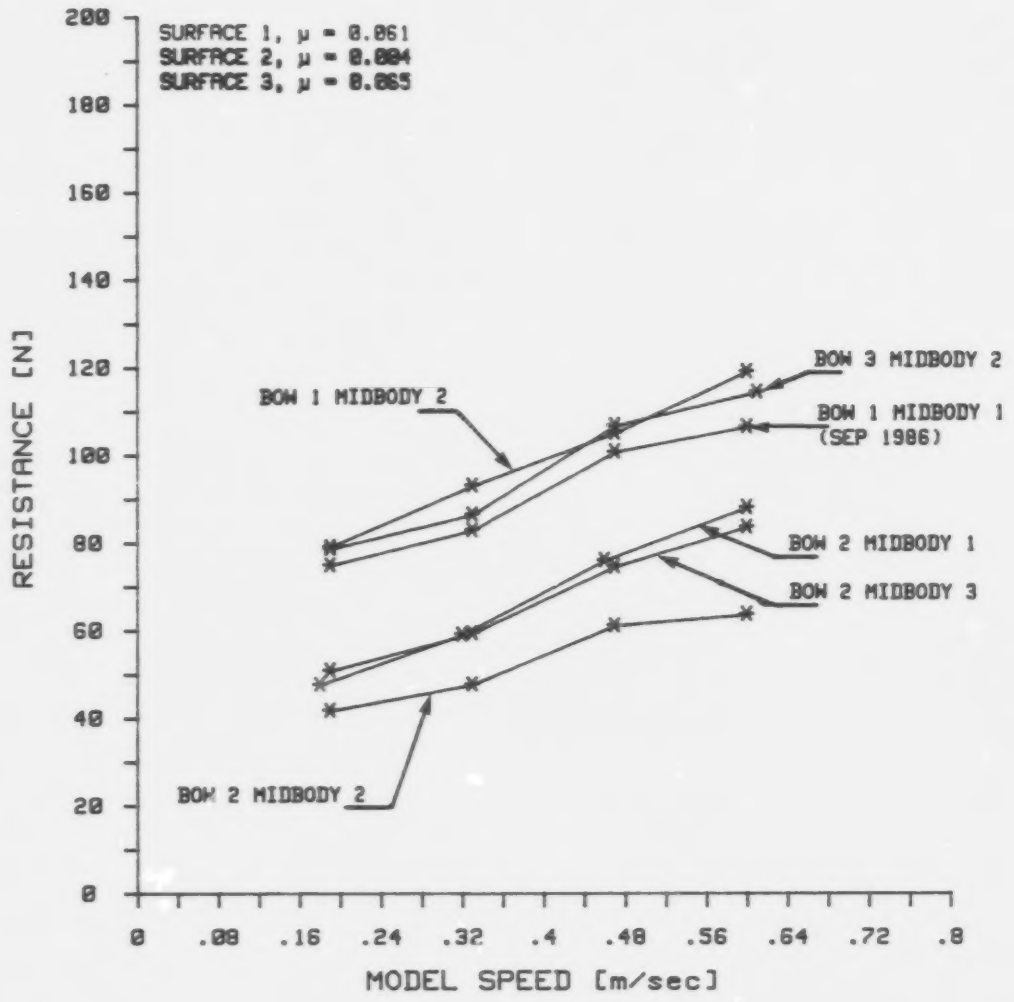
1. The smooth surface, surface 2, resulted in significantly lower resistances across the speed range than the middle roughness, surface 1. Figure 4.11 represents the corrected resistance values for the middle surface on the whole model and the smooth surface on the whole model. It can be seen that the reduction in resistance, resulting from the friction coefficient changing from 0.061 to 0.004, is approximately 45% and, within 3%, remains constant over the speed range.

2. Figure 4.11 also shows the resistance data from the other combinations including the middle and smooth surface. The effect of changing the midbody only from the middle surface to the smooth surface does not result in a significant reduction in resistance, however, changing the bow does have a significant effect and reduces the resistance by about 30%. The reduction is not consistent across the speed range and changes from about 40% at low speed to 30% at the higher speed. This is true for both the middle surface and the first rough surface, as shown on the figure, and further enforces the assumption that these two friction coefficients are effectively the same.

3. The speed dependency difference between the totally smooth model and the model with the middle or rough surface on the bow and the smooth surface on the midbody would indicate that the influence of the friction on the midbody is higher at lower speed and becomes less significant at higher speeds. Considering the sample data that has been collected (Forland and Tatinclaux 1985) it may have been expected that, for the middle surface and first rough surface, the effective friction coefficient would reduce significantly in the speed range from 0.05 to 0.2 m/sec and that for the smooth surface the friction coefficient would be unaffected by speed.

FIGURE 4.11

COMPARISON BETWEEN FRICTION COEFFICIENTS ON THE ARCTIC BOW AND MIDBODY



Target Strength = 19 kPa
Target Thickness = 50 mm
Friction coef. = .004 .061 and .065

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This should manifest itself as a lower influence of friction on the resistance over this speed range for the middle and rough surface and little or no influence on resistance for the smooth surface. Unfortunately the referenced data does not include speeds over the same range as the model tests although they do suggest that above 0.25 m/sec the friction coefficient becomes constant with speed. This general result agrees with the resistance data collected from the model tests, with the exception that during the model tests the effect appears to be occurring over a higher speed range. Additional higher speed model tests are required before any conclusion can be made with regard to the point at which the effect of friction coefficient becomes constant for the middle or first rough surface.

4. The presawn are shown in Figure 4.12. It can be seen that the same trends that were observed in the level ice tests may also be observed in the presawn tests. The lowest presawn resistance is associated with the smooth bow and midbody combination. The effect of fitting either the middle, or first rough surface, midbody is to slightly increase the resistance. The models with the middle and first rough surface on the bow and midbody result in the highest resistance. However the difference in resistance between the models with the different friction coefficients is significantly less with the presawn tests than with the level ice tests. This indicates that the friction forces that will occur at the bow of the model whilst breaking are larger than those associated with only displacing the ice to one side.

   This result may indicate that the effectiveness of a low friction coating is predominantly at the bow water line and that the majority of benefit can be achieved by only treating this area.

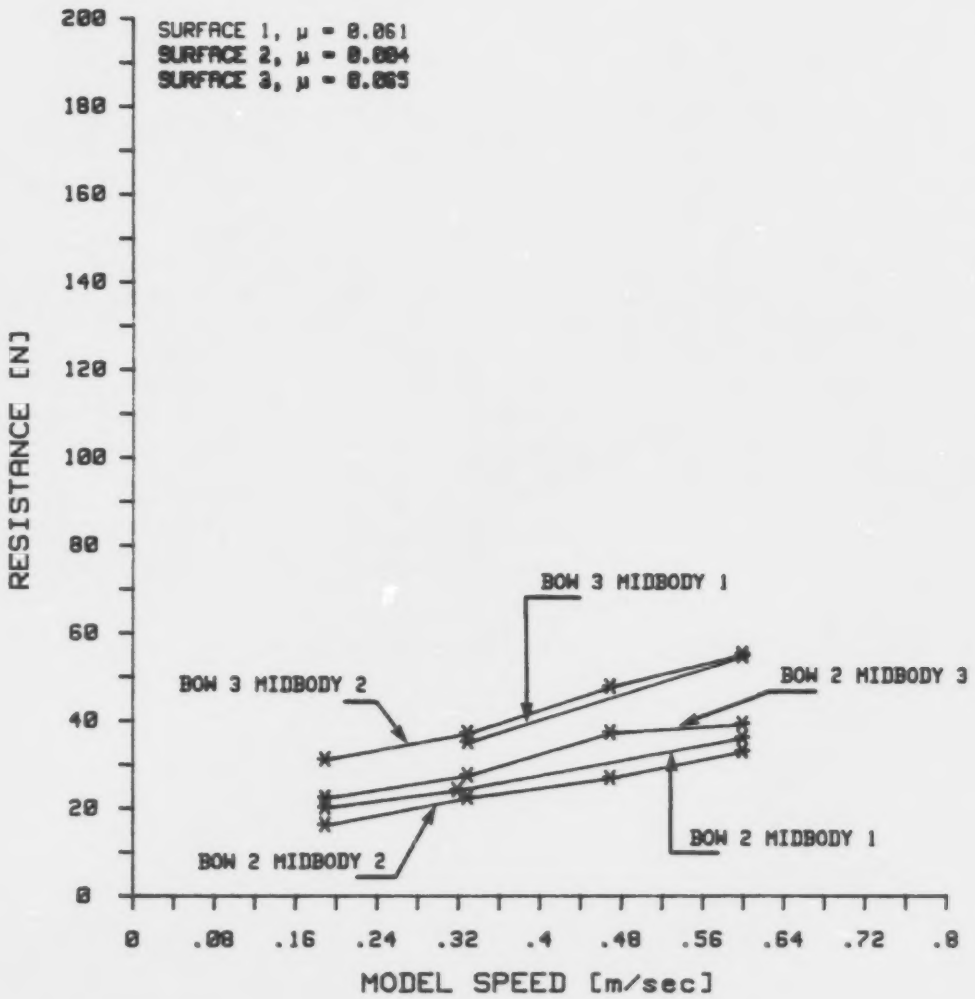
c) Middle roughness compared with the final rough surface

1. During the second series of tests in October 1978 the model was tested with the middle surface, surface 1, on the bow and stern and the high friction coefficient, 0.354, on the bow. The results of these tests are shown in Figure 4.13. Both of the model tests with the middle surface (September 1986 and October 1987) are shown in the figure and it can be seen that the October 1987 tests tend to have a slightly higher speed dependency than the earlier test in September 1986.

2. The higher friction coefficient results in a significantly higher resistance. Unfortunately, tests were not conducted with a rough, 0.4, midbody that be used as a comparison with these tests.

FIGURE 4.12

COMPARISON BETWEEN FRICTION COEFFICIENTS ON THE ARCTIC BOW AND MIDBODY - PRE SAWN TESTS



Target Strength = 19 kPa
Target Thickness = 50 mm
Friction coef. = .004 .061 and .065

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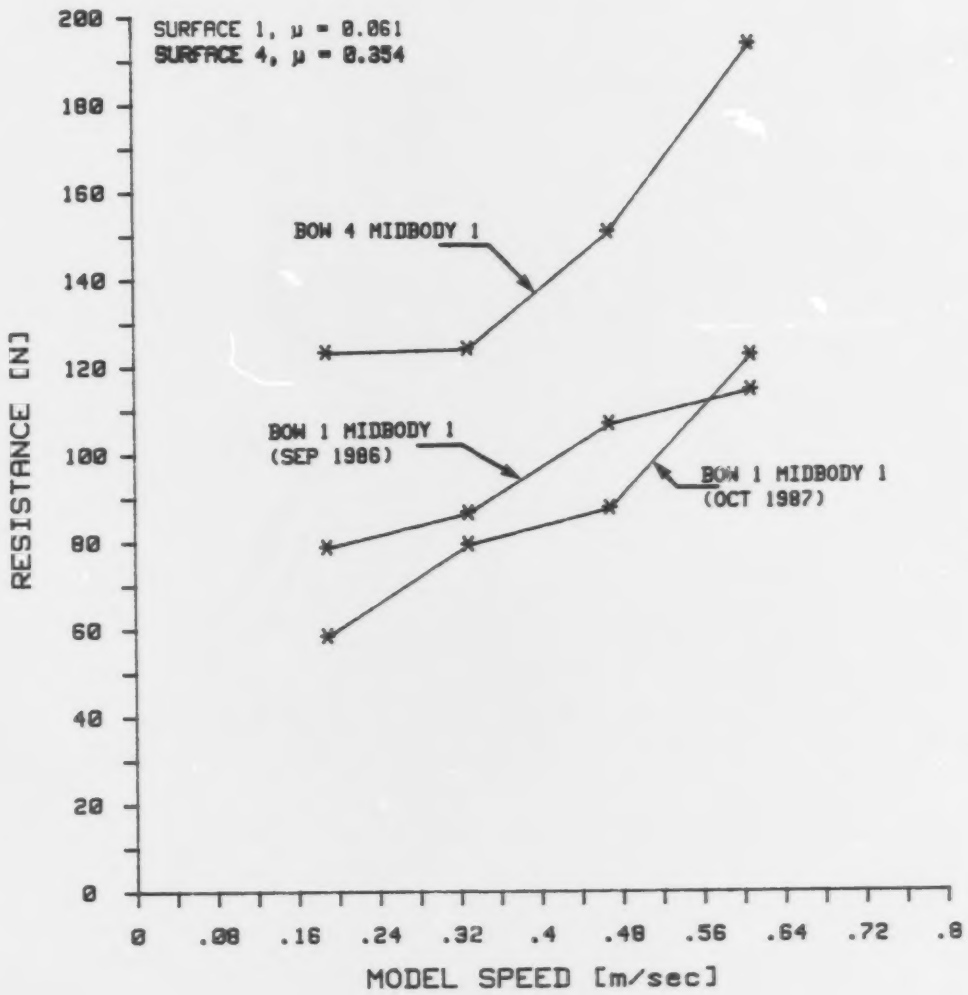
FIGURE 4.13

COMPARISON BETWEEN FRICTION COEFFICIENTS ON THE ARCTIC BOW AND MIDBODY



Target Strength = 19 kPa
Target Thickness = 50 mm
Friction coef. = .354 and .061

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5. CORRELATION ANALYSIS

5.1 General

The ARCTIC model that has been used during these tests was also used during three other test programmes in Canada and Europe. In addition full scale results have now been made available from the trials of the ARCTIC during 1986. In order to compare the result from the IMD model tests with these other tests it has been elected to compare the model test values at model scale and then convert the data to full scale for comparison with the full scale trial results.

5.2 Model Test Comparison

The model of the ARCTIC has been tested at the HSVA facility in Hamburg, the WARC facility in Helsinki, and Arctec Canada Ltd in Ottawa. The details of these tests have been reported (Baker 1985). The comparison between the tanks will be based on Resistance values since these were the form of the tests in IMD. The tests in HSVA were only self propulsion, and these have been converted to resistance values by calculating the nozzle thrust (which was not measured during the HSVA tests) and assuming an open water thrust deduction. The details and discussion of the assumptions have been published in the original test report (Melville 1986). Although the WARC results were multiplied by conversion factors for the final prediction, the data presented here is based on the corrected measured resistance before any conversion and correlated to the measured friction coefficient. The results of this comparison are shown on Figure 5.1. Unfortunately the tests were undertaken at different friction coefficients and thickness so the comparison is not clear.

Figure 5.1 may also be plotted as resistance vs. the log of friction coefficient. This is presented in Figure 5.2 based on a speed of 0.2 m/sec. Although there does appear to be some consistency with the IMD data the remaining data from the other model tanks does not conform in a similar way and underlines the need to ensure consistent testing procedures and techniques. It would clearly be valuable to establish if the relationship demonstrated for the 50 mm ice in Figure 5.2 can be confirmed for the thinner 40 mm ice based on the same model and test procedures.

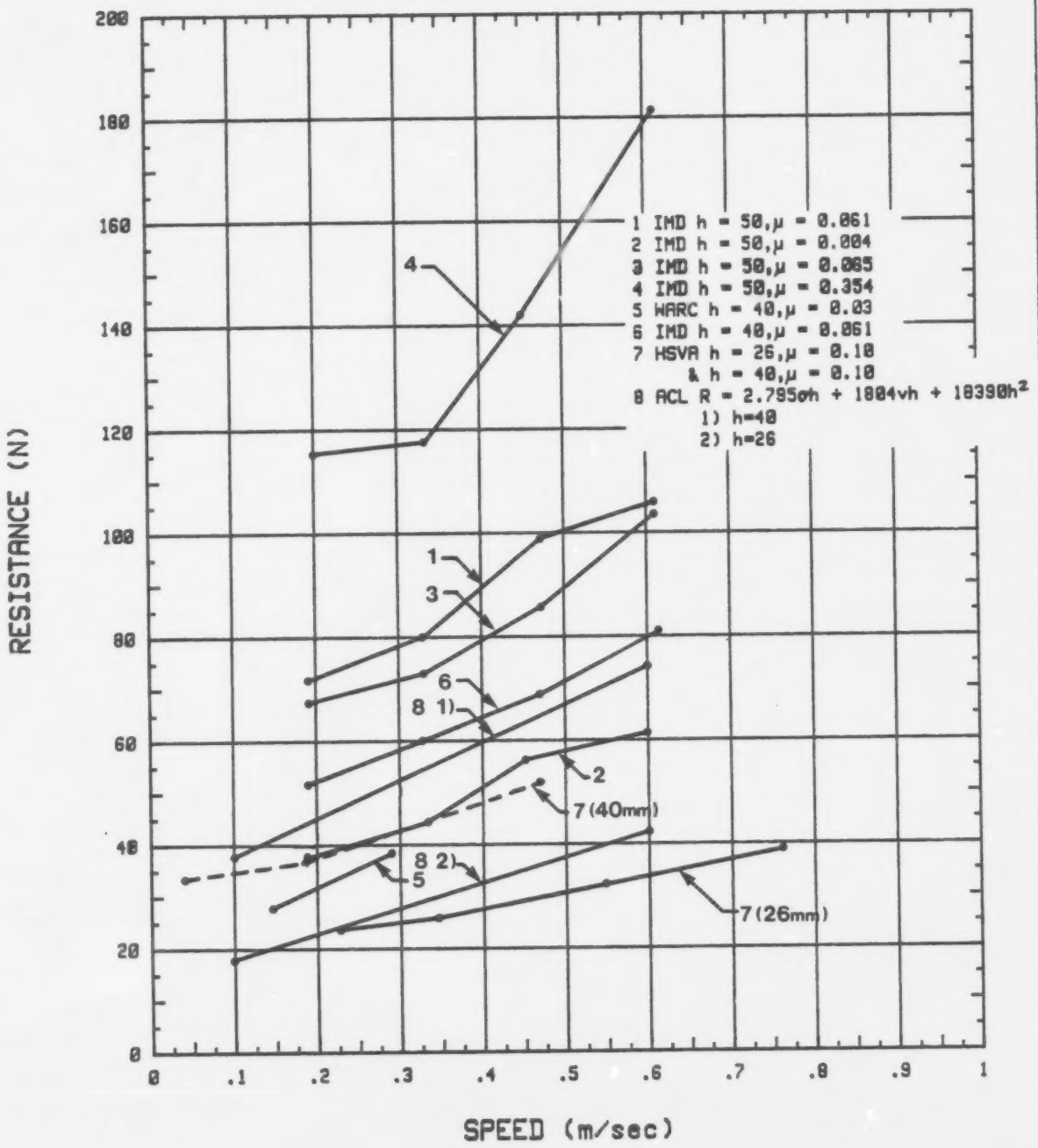
5.3 Full Scale Comparison

The results of the data may also be compared with the full scale data. The IMD and WARC model tests were only conducted in the resistance mode and as a result the data from these tests are modified to required thrust by using the open water thrust deduction fraction. The comparison is shown in Figure 5.3

Figure 5.3 represents the ship speed against ice thickness for all the model tests and the full scale performance of the Arctic. The results presented from each of the tanks is the full scale prediction of the model using their own prediction technique. For example the WARC data includes

FIGURE 5.1

COMPARISON OF MODEL TEST RESULTS
FROM WARC, HSVA, ACL AND IMD



RESISTANCE CORRECTED TO : STRENGTH = 16.7kPa
THICKNESS = 50mm, 40mm & 26mm

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FIGURE 5.2

RESISTANCE VERSUS LOG FRICTION COEFFICIENT

FOR HSVA, WARC, ACL AND IMD

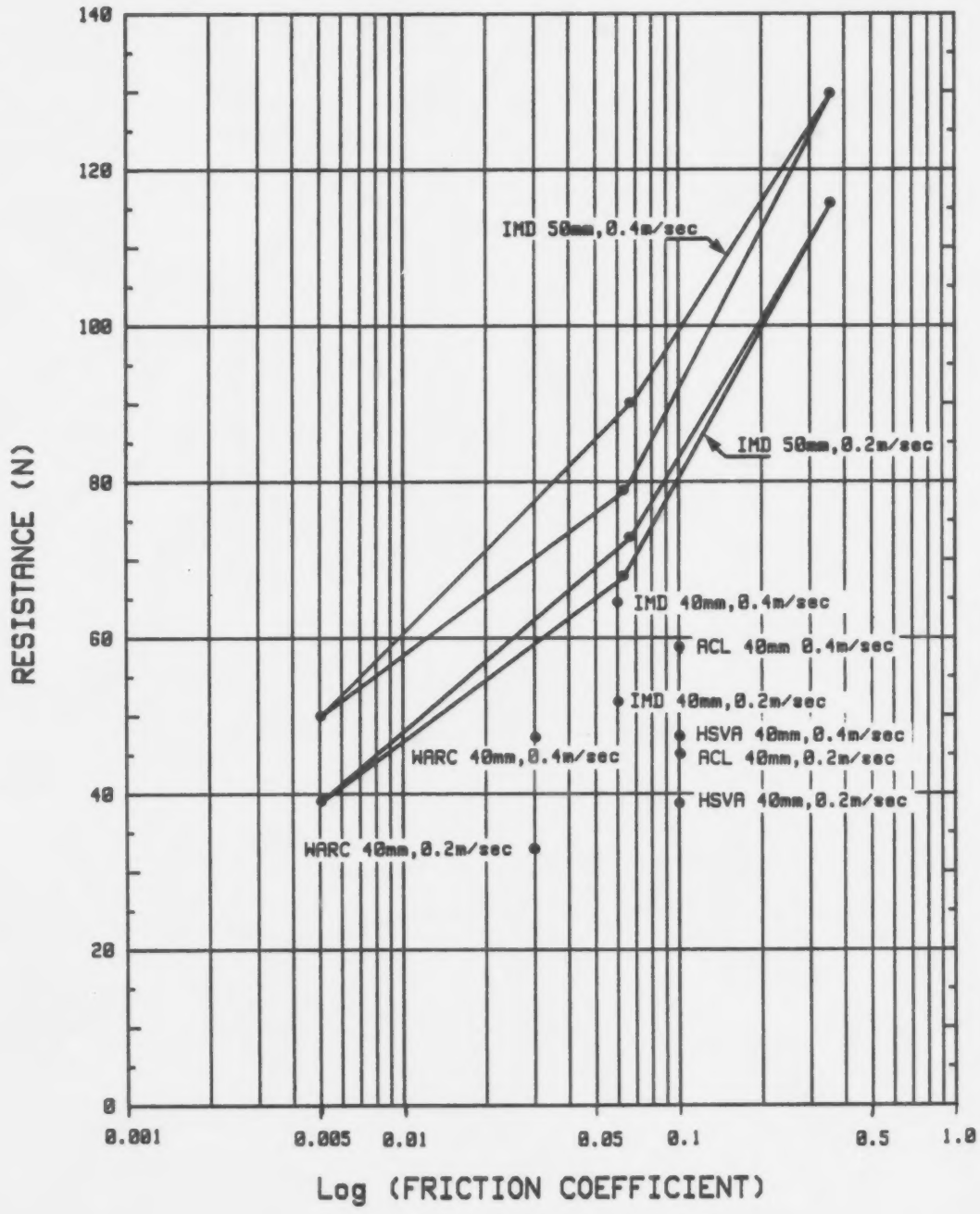

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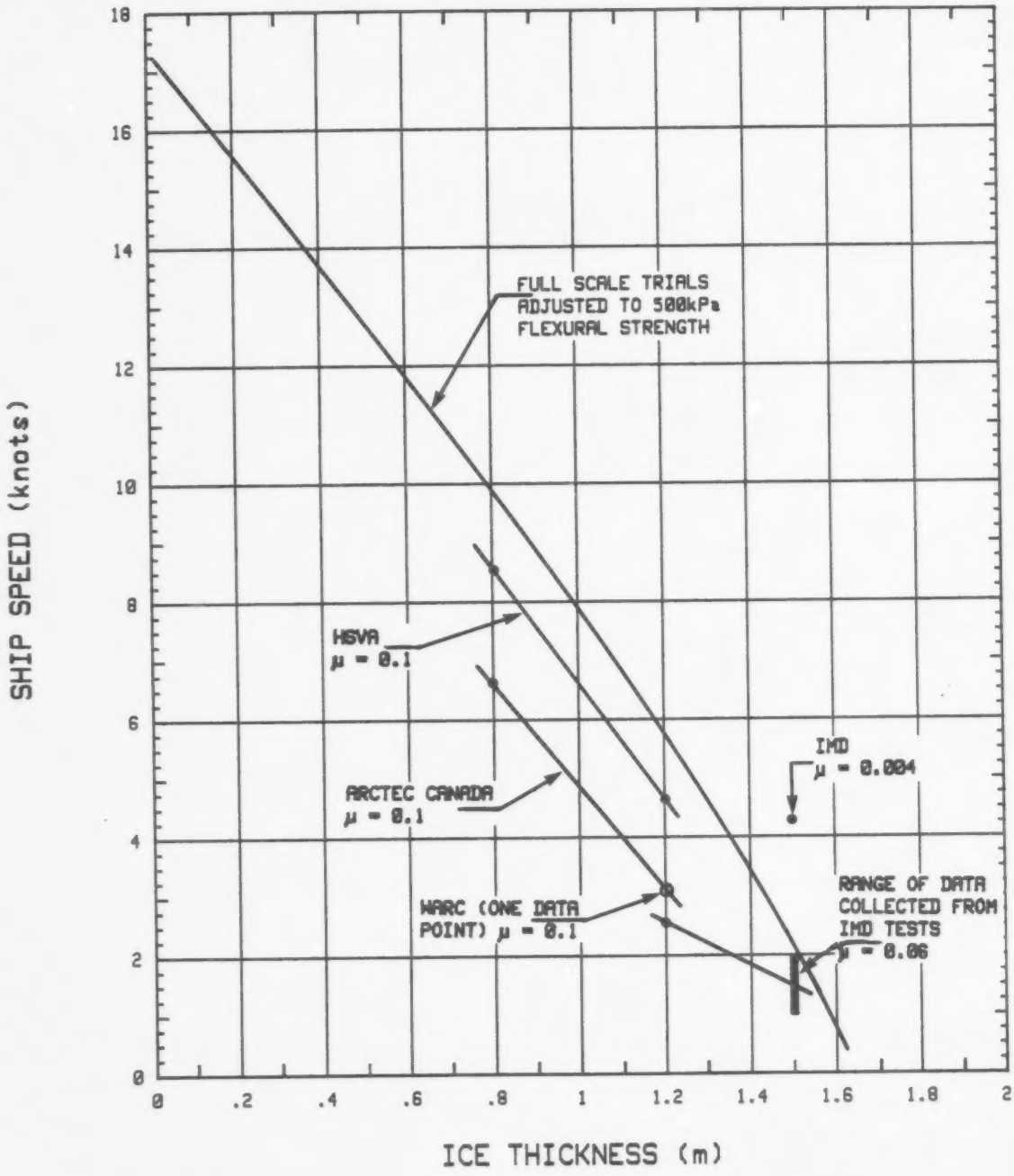
FIGURE 5.3

MV ARCTIC - SPEED VERSUS ICE THICKNESS
COMPARISON OF MODEL AND FULL SCALE RESULTS



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the 1.29 friction correction factor. The scatter of data is predictable and, as observed after the full scale trials, the HSVA prediction was the closest to the tested performance. It can be seen from this figure that, at a scale of 1:30 and in 50 mm ice, the IMD tank appears to predict the performance of the Arctic when the model has a friction coefficient of about 0.06. In thinner ice the same friction coefficient does not conform with the full scale or model scale trends of speed versus ice thickness. The reason for this is unclear but should be examined further with additional model tests at the thinner ice thickness.

6. CONCLUSIONS

The conclusions of this model test programme may be summarised as follows;

a) A review of the literature highlights the significance of the friction coefficient. Model and full scale tests have shown that the coefficient is dependent on the normal force, the type and roughness of the hull surface and the type and condition of the ice surface. Although it has been shown that rougher surfaces, of the same type, result in higher friction coefficients dissimilar surface types may reverse this trend and result in smoother surfaces having higher friction coefficients. Clearly the testing methodology and conditions of the test are of paramount importance both for full scale and model scale tests.

b) The surface definition tests conducted with the friction jig resulted in test results compatible with those recorded by previous researchers.

c) The model tests of the friction coefficient were conducted at IMD over a period of a year. A repeated test from one test period did not conform well to the same test conducted a year later and although this is a significant period of time it does indicate that the ice mechanical properties may have changed although the standard measuring techniques did not recognise any difference between the ice sheets.

d) The first rough surface tested as part of the September 1986 tests were not distinguishable from the middle surface and resulted in a second rough surface, which was tested in October 1987.

e) The influence of the friction coefficient is significantly stronger at the bow, than on the midbody. The tests have shown that the influence of varying the friction coefficient on the midbody is negligible compared to increasing the friction coefficient on the bow. A reduction in the friction coefficient on the bow from 0.06 to 0.004 resulted in 45% reduction in resistance.

f) The results of the IMD test programme indicate a different ice thickness dependence than any other tank, and full scale.

g) the test data recorded for a friction coefficient of 0.061, the middle surface, correlated very closely to the full scale performance of the Arctic.

h) Subsequent tests of the same model in ice sheets with measurably identical ice properties resulted in significant variations in the Resistance. This variation is considered to be due to different ice mechanical properties that were not recorded during the test, such as crushing or shear strength.

7. RECOMMENDATIONS

As with any research project, the information gathered during the tests identifies areas that require further work. These may be summarised as;

1. Additional thinner ice sheets should be tested to clarify the apparent lower dependency of resistance on ice thickness, shown during the IMD tests.

2. Additional work should be done to test the new rough surface on the midbody of the ARCTIC to confirm the low influence of midbody friction on resistance at this higher friction coefficient.

3. The mechanical properties of the ice are believed to be responsible for the non conformity between two identical tests. Additional work should be done to establish a better method to measure the properties of an ice sheet more thoroughly. An instrument called the INDEXER is currently under development by Melville, IMD and TDC that will be capable of monitoring the flexural, shear and crushing strength of the model ice.

4. The current tests have been undertaken with one type of bow. To confirm whether this relationship is bow form dependent another set of tests should be conducted on a second type of bow form. The recent, unpublished, results of the R-Class tests in a number of different tanks should be reviewed to asses the value of this work.

5. Additional lower speed tests should be run to investigate the very low speed effect of friction, identified during full scale trials by Makinen.

6. Additional friction tests should be conducted on the test panels using higher normal forces, or smaller test samples. Preparation for this work is currently under way at IMD where structural modifications are being made to the friction jig to support higher normal loads.

7. Additional friction tests should be conducted on the test panels using different orientations of ice/surface interface. Tests should also be conducted to validate the quadratic equation form or the friction coefficient definition. These should include tests with 'standard' surfaces to calibrate the equipment and develop relationships between the surface morphology and friction coefficient.

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APPENDIX 1

INFORMATION SOURCE SUMMARY SHEETS

TITLE: On the Role of Bow Friction in Ice Breaking

AUTHOR: Scarton, H. A.

SOURCE: Journal Of Ship Research
VOL.19 N°1 March 1975

ABSTRACT:

The influence of frictional resistance on the icebreaking process is studied. A mathmatical expression is developed that presents an analysis of the Friction Coefficient based on its direction of application.

REVIEW AND COMMENTS:

By using a mathematical representation of an icebreaking bow it is shown that the efects of friction on the bow are highly directionally dependant.

TITLE: Influence of Friction on Ice Resistance: Search for Low Friction Surfaces

AUTHOR: Makinen, E.,Lahti, A. Rimppi, M

SOURCE: Ice Tech Symposium
Montreal Canada 1975

ABSTRACT:

The influence of the hull surface quality is measured both at model scale and full scale. Some coating systems are reviewed and stainless steel is proposed as a smooth surface for ice breaking regions on the ship.

REVIEW AND COMMENTS:

Based on full scale results of the ice breaking tug, JELPPARI with and without a stainless steel belt, the total resistance of the tug was found to be strongly dependant on the Friction Coefficient, particularly at the lower speeds.

Tests were conducted with the Finnish Coast Guard cutters SILMA and VALPAS in which the ships were tested before and after major hull surface refurbishment. The results of the tests indicated the strong dependance of hull surface roughness on the performance of the ships.

Different hull surface coatings were tested on the MURTAJA and JERMAK. Of the coatings tested the Solvent free Epoxy was the only surface that was not damaged.

The influence of friction at model scale is discussed and general trends illustrated from previous test series.

TITLE: Impact Forces and Friction Coefficient on the Forebody of the German Polar Research Vessel Polarstern.

AUTHOR: Hoffmann, L.

SOURCE: Internal report by HSVA
1986

ABSTRACT:

The German Polar Research vessel Polarstern was fitted with instrumentation to measure the normal and tangential forces acting on two panels in the bow of the ship. The report sumarises the instrumentation arrangement and presents the results of the full scale trials conducted off the coast of Labrador in May 1984.

REVIEW AND COMMENTS:

Two load cells, one close to the stem and one at the shoulder, were built into the bow of the Polarstern and monitored during full scale trials in May 1984 off Labrador. Each panel was 1.12 m^2.
The level ice thickness during the tests was 0.7 - 1.5 m, and the flexural strength 250 - 350 kPa.
The max loads recorded during the tests occured during level ice transiting.
The highest recorded force was 2,800 kN (Normal Force).
The normal forces recorded during the tests are presented below;

Ice Condition	FRONT POCKET		SHOULDER POCKET	
	Mean	98% Max	Mean	98% Max
Level Ice	386	1500	357	1400
Broken Channel	141	600	137	700
Manoeuvring	306	800	296	700
Pack Ice	278	1000	362	1200
Ramming	299	1100	263	900
Total	302	1000	339	1100

The associated Friction Coefficients are;

Ice Condition	Friction Coefficient	
	Front Pocket	Shoulder pocket
Level Ice	0.164	0.171
Broken Channel	0.224	0.286
Manoeuvring	0.187	0.176
Pack Ice	0.128	0.146
Ramming	0.191	0.253
Total	0.139	0.166

The Friction Coefficient decreased from about 0.25 to 0.08 as the normal force increased to 1500 N (1,339 kPa). The Friction Coefficient tends to level off at about 0.1 at 800 N (714 kPa) and then drops again at about 1700 N to .06. There is some evidence that above 2000 N the Friction Coefficient increases with normal force.

The influence of speed was investigated during the level ice tests. Ship's speed was used to define the ice/hull interface speed. The results from the front pocket were different from the shoulder pocket. The Friction Coefficient at the front pocket showed no influence from speed. The Friction Coefficient at the shoulder pocket increased with ship speed linearly. The variance between the results is thought to be either the different normal forces on the two panels or the influence of assuming ship speed instead of ice/hull speed.

No attempt to investigate the effect of pressure because of the real contact area between the ice and panel is not known.

TITLE: The Mechanism of Friction of Ice

AUTHOR: Oksanen, P.

SOURCE: Wear 78 (1982) 315-324

ABSTRACT:

The kinetic Friction Coefficient between ice and ice was measured over a range of temperatures and loads. The Friction Coefficient between ice and some other material is calculated assuming that the Friction is caused by a water film.

REVIEW AND COMMENTS:

Friction tests were conducted with samples moving on a circular bed of ice. Different normal forces and speeds were used at different temperatures.

The results of the experiments show that the coefficient of Friction;

- Tends to reduce as temperature increases from -15°C to -1°C.
- Reduces with increased speed at low temperatures (-15°C).
- Increases with increased speed at higher temperatures (-1°C).
- Tends to decrease with increasing normal force.

An equation is developed that is shown to be capable of predicting the correct order of magnitude for the Friction Coefficient based only on the water film and not including factors such as scratch formation.

TITLE: Model and Full Scale Tests with an Innovative Icebreaking Bow

AUTHOR: Enkvist, E. ; Mustamaki, E.

SOURCE: SNAME AGM Transactions 1986

ABSTRACT:

A series of non shipshape bows were designed to establish a bow form uncompromised by open water considerations. The bow was model tested in the WARC ice tank. The bow was then built as an attachment to the salvage tug 'PROTECTOR' and full scale tests conducted to investigate the full scale performance of the new bow. Hull instrumentation was built into the new bow to investigate the hull/ice friction effects.

REVIEW AND COMMENTS:

Instrumentation panels were located in the bow and bottom of an experimental bow attached to the ice breaking tug Protector. Full scale testing was completed in 30 - 69 cm ice with a flexural strength of 324 - 714 kPa, a horizontal crushing strength of 1.3 - 2.5 MPa, a vertical crushing strength of 2.4 - 3.04 MPa and a modulus of 4.79 - 6.5 GPa.

The panel at the bow experienced higher pressures and gave lower value of Friction Coefficient than the bottom panel. The measured average Friction Coefficient for the bow panel varied from 0.045 in a broken channel to 0.13 in snow covered level ice. The average values for the bottom panel were between 0.157 for the broken channel and 0.255 for the snow covered level ice.

Experiments were conducted with the snow cleared off the level ice and after wetting the snow Friction Coefficient at the bow and bottom panels were not affected.

The difference in Friction Coefficient between the bow and bottom panels was attributed to pressure differences experienced by the two panels.

TITLE: Kinetic Friction Coefficient Of Ice

AUTHOR: Forland,K.A.
Tatinclaux,J.C.

SOURCE: US Army Corps of Engineers CRREL Report # 85-6
1985

ABSTRACT:

The report reviews past work related to the Friction Coefficient, then describes a series of experiments that investigate the effects of the ice characteristics of strength, hardness, and test configuration, etc. on the Friction Coefficient.

REVIEW AND COMMENTS:

A series of tests conducted on samples of laboratory grown ice and different materials concluded that;

a) There is no scale affect due to sample size
b) There is no affect due to difference between sample of ice moving on material and material moving on sample of ice.
c) There is a significant affect due to difference between sample of ice moving on material and sample of material moving on ice.

For the Ice sample on the sheet of material;

1) Increased ice hardness results in lower Friction Coefficient at constant pressure.
2) Friction Coefficient reduces rapidly as normal pressure increases to about 10 kPa, above about 15 kPa there is no variation in Friction Coefficient as pressure increases (Stainless steel sample, hardness 1975 kPa, 10 cm/sec).
3) Friction Coefficient increased from .03 to .07 with a sample speed of 5 to 25 cm/sec. on smooth stainless steel (.33 um RA).
4) The orientation of the ice sample sliding over stainless steel (.36 um RA) has little affect on the Friction Coefficient
5) The Friction Coefficient increases rapidly from about .04 to .2 for a small increase in roughness from .5 to 1 um RA and remains about constant above 1 um RA to 7 um RA (ice hardness 1975 kPa, 10 cm/sec, 10 kPa).

For samples of material on a sheet of ice;

1) Samples of Stainless Steel (.33 um RA), Aluminium (0.3 um RA) and Inerta 160 (1.6 um RA) were tested over a speed range of 5 to 25 cm/sec. No speed affect was found although Inerta 160 with the roughest surface showed the lowest Friction Coefficient.

2) The Friction Coefficient remains constant or reduces slightly when a smooth material sample (.33 um RA) slides over ice at increasing speed from 5 to 25 cm/sec.
3) Friction Coefficient reduces significantly for a rough steel sample (1.5 um RA), sliding over ice from 5 to 25 cm/sec. This indicates the importance of surface morphology and the conduction of frictional heat away from the sliding surfaces when compared to the Inerta 160 result.
4) Using Aluminium and steel samples with a roughness increasing from .03 to 2 um RA the Friction Coefficient increased rapidly from about .04 to .11. Above 2 um RA the Friction Coefficient reduced to about .08. The tests indicated that the morphology of samples with the same roughness affects the Friction Coefficient.

No satisfactory explanation is proposed for the variance between speed dependancy for different test configurations. However it is suggested that it may be related to the thickness of the water layer between the two materials. For a sample of ice sliding over stainless steel it is proposed that, due partly to brine drainage and asperity melting, the water layer between the surfaces will be thicker than if the stainless steel sample slides over ice. This will result in higher dependance on the viscouse shear forces and the Friction Coefficient will vary as the square root of the speed as shown in the results.

The speed dependance of the rougher steel sample is considered to be caused by the penetration of the water layer by the sample asperities at lower speeds. At higher speeds the water layer will be thicker and no penetration will occur.

The frictional shear stress Fst. of ice sliding over a smooth stainless steel surface is a linear function of normal pressure, P, applied to the ice sample;

$$Fst = A * P + C$$

where: A = Constant
C = Y intercept of Fst versus normal pressure.

Both "A" and "C" are decreasing functions of the ice hardness. When the hardness reaches a critical value "C" becomes negligable and "A" becomes a constant. The results imply that the Friction Coefficient decreases as hardness and normal load up to a critical value of hardness. Above this critical value the Friction Coefficient is independant of both hardnes and normal load.

TITLE: Results of Trials in Ice and Open Water of the CCGS Pierre Raddison

AUTHOR: Arctec Canada Ltd

SOURCE: Canadian Coast Guard Fleet Systems;
Report #245C-8, November 1979

ABSTRACT:

This report describes the results of full scale trials on the CCGS Pierre Raddison in open water and ice during 1978-9. The ice trials were conducted South of Victoria Island in the Canadian Arctic during July and August 1978 and in the St. Lawrence River, the Saguenay River and the Gulf of St. Lawrence during February 1979.

REVIEW AND COMMENTS:

The Friction Coefficient was measured on the side of the Pierre Raddison using an "Ice Tribometer". This device consists of an instrumented sample carrier supported by a radial arm pivoting horizontally from some position on the ice adjacent to the ship. The device is positioned so that when the arm is rotated the ice sample is be dragged/crushed against the hull surface.

The results of the Arctic Summer (1978) tests were:

- Normal forces not reported
- Abraded section of hull (bare steel and painted
- Surface roughness: bare steel 7.3 um $\pm$ 2 CLA
  : painted steel 4.2 um $\pm$ 2 CLA
- Friction Coefficient: bare steel $v < 0.5$ m/sec $fk = 0.3 \pm 0.07$
  bare steel $v < 3.5$ m/sec $fk = 0.19 \pm 0.12$
- Friction Coefficient for painted steel not required.

The results of the winter (1979) saguenay and St. Lawrence River tests were:

- Normal forces up to 4083 N
- Friction Coefficient not significantly affected by speed
- Surface roughness: bare steel 16.48 um $\pm$ 3.4
  : painted steel 7.82 um $\pm$ 1
- Friction Coefficient: bare steel $v = 0$, $fk = 0.28 \pm .03$
  bare steel $v >$ $fk = 0.21 \pm 0.035$
  painted steel $v = 0$, $fk = 0.19$
  painted steel $v >$ $fk = 0.09 \pm 0.02$

The tests indicated that the Friction Coefficient increased with roughness and the knietic Friction Coefficient is higher than the dynamice.

For surfaces of equivalent roughness; 1978, Baresttel, 7.3 um CLA and 1979 7.82 um CLA, significantly different Friction Coefficients were recorded, 1978 - 0.3 $\pm$ 0.07 and 1979 , 0.09 $\pm$ 0.02. This was attributed to different ice conditions.

These results were compared with laboratory tests in low, medium and high salinity ice at-10°C, against samples of Zebron 386 and Inerta 160;

- Zebron 386 (22u CLA); f_k= .008 - .02 f_s= .03 - .038
- Inerta 160 (89 uCLA); f_k= .015 - .032 f_s= .042 - .056

No description was given of the laboratory tests which showed a reduction of Friction Coefficient as a function of solinity (high salinity - high friction) and speed (low speed - high friction).

TITLE: Arctic Deployment of USCGC Polar Star - Winter 1982
Volume III, Polar Class Performance: Trafficability, Level Ice and Pressure Ridges.

AUTHOR: Arctec Incorporated

SOURCE: Marine Administration U.S. Department of Transportation
November 1982

ABSTRACT:

Environmental and ship performance data were collected in the Bering and Chukchi Seas whilston board the USCGC Polar Star in April and May 1982.

REVIEW AND COMMENTS:

The Friction Coefficient was recorded using two methods; Ice samples held at the end of a horizontal radial arm, pivoted at some point adjacent to the ship, so that when the arm was rotated the ice sample was brought against the ship's side in a crushing/sliding action; ice samples were held in a carriage positioned on a rail system adjacent to the ship's side, when the carriage was moved along the rail the ice sample was dragged horizontally along the hull.

The results from the rotating arm tests were widely scattered ranging from .052 to .343, the average calculated friction factor was 0.2. This was considered high and inconsistant with previouse work.

The rail and carriage system produced values ranging from .027 to .076 with an average of .076. These were considered to be consistant with previous years tests. Unfortunatly no details of these tests are presented.

From the rotating arm tests with cold hard surface ice;

- Peak normal force ranged from 258 lb (1,148 N) to 1291 lb (5,743 N)
- Average peak foce was 641 lb (2,851 N)
- The data showed no dependancy on speed
- The data showed no dependancy on normal force.

TITLE: Full Scale Testing in Ice of Three Icebreakers

AUTHOR: German, G.J.
Lawrence, R.G.A.

SOURCE: Society of Naval Architects and Marine Engineers
ICE TECH Symposium Montreal Canada 1975

ABSTRACT:

The full scale tests of three icebreakers are reported; The CCGS Wolfe tested in 1969; The Louis S St Laurent tested in 1970 and; The Labrador tested in 1973.

REVIEW AND COMMENTS:

No friction measurement were reported for the Louis S St Laurent tests. During the CCGS Wolfe tests the Friction Coefficient was measured using a 1/4" steel sled on newly fallen and hard crusty snow at -3 to -1°C. No influence of the different surfaces were identified during the higher load tests, in lower load tests the new snow surface demonstrated from 50 to 100% higher Friction Coefficients. Tests were carried out over a range of loads. The kinetic Friction Coefficient was about 0.1 and independant of load for the dry crust snow, no reference was made to the sample speed. The static Friction Coefficient was higher ranging from .3 to .55, generally the static friction increased with the higher loadings.

TITLE: Evaluation of Two Icebreaker Hull Coatings for Arctic Petro Carrier Project

AUTHOR: Calabrese,S.J.

SOURCE: Melville Shipping Ltd.
Restricted Distribution

ABSTRACT:

A programme of laboratory tests were conducted on two hull surface coatings, Inerta 160 and Zebron. Friction tests were conducted on the samples over a range of speeds and normal loads from 0 to 20 knots and upto 300 psi (2068 kPa)

REVIEW AND COMMENTS:

The friction tests were conducted using a drill stand and sample holder. The samples of test material were rotated on top of the ice sample at different speeds and under different temperatures and pressures. The two specimens used were Inerta 160 (68 u CLA) and Zebron (110 u CLA). The results of the tests are;

- For Inerta 160 at -5°C the friction varied between 0.25 at 345 kPa and 0.19 at about 1034 kPa for higher loads up to 2068 kPa the friction increased to 0.3. During the lower temperature tests at -10°C the friction varied in a similar fashion from 0.16 to 0.09 up to 689 kPa, it was then constant above this pressure up to 1724 kPa and increased to 0.16 at 2068 kPa. Ice damage was observed during all the higher temperature tests but only at 2068 kPa during the low temperature tests.

  As a function of speed and at a normal pressure of 1034 kPa, the friction at -5°C, increased from 0.18 at 2.6 m/sec to 0.3 at 10.3 m/sec. At -10°C the friction remained at .1 from 2.6 - 7.72 m/sec and then increased to .14 at 10.3 m/sec. Ice damage was observed during all the higher temperature tests but not during the lower temperature tests.

  The Zebron tests showed similar pressure variation trends. At -5°C the friction started at 0.2 for 345 kPa and decreased to 0.15 at 1034 kPa, then increased to 0.2 at 2068 kPa. At -10 °C the friction dropped from 0.16 at 345 kPa to 0.06 at 689 to 1379 kPa and then increased to 0.11 at 2068 kPa

  As a function of speed and normal pressure of 1034 kPa, the friction at -5°C, increased from 0.1 at 2.6 m/sec to 0.19 at 10.3 m/sec. At -10°C the friction decreased from .07 at 2.6 m/sec to .06 at 10.3 m/sec.

Tests were also conducted with flooded samples of Inerta and Zebron. The results for the Inerta sample were only slightly less than from the dry values. The results from the Zebron sample showed a significant reduction.

TITLE: On the Resistance Encountered by Ships in the Continuous Mode of Icebreaking

AUTHOR: Enkvist, E.

SOURCE: The Swedish Academy of Engineering Sciences in Finland Report #24 , 1972

ABSTRACT:

A review of the performance prediction techniques for ice breakers. The report compares model and full scale data for a number of icebreakers together with model and full scale analysis of the Coefficient of Friction.

REVIEW AND COMMENTS:

Full sale and model test results are presented in the report;

The full scale sample tests were conducted with a 0.65 m x 1.62 m sledge loaded with weights to give a range of pressure from 1.3 to 20 kPa. The ice was .9% saline partly clean partly covered with light snow and partly covered with wet snow. The air temperature was -5°C.
Results from the tests with a surface pressure of 10 kPa speed .5 m/sec were;

Material	Ice	Snow	Wet Snow
Stainless steel, smooth	.025	.099	.066
Aluminium, smooth	.033	.089	.069
Smooth painted steel	.041	.129	.101
Sandblasted steel	.045	.189	.036
Rough scrap steel	.109	.307	.141
Static Friction, 20 kPa; Sandblasted steel	.34	.52	.32

Experiments were also conducted in the laboratory using a metal plate from .051 to .096 m^2 with an applied pressure of .53 - 7.89 kPa.

The results of the tests were reported to be;

- Dry snow increases the kinetic friction by about a factor of 4 over dry ice
- Wet snow produces about the same values as dry ice.
- The kinetic friction of sandblasted steel on dry ice is 0.05 for high loads.
- No scale affects were observed between the full scale and laboratory tests.

- Friction is independant of velocity, even on wet ice, indicating no influence from viscosity forces.
- Friction is independant of load above about 15 kPa.

Additional sample tests were conducted on a much rougher surface over a wider pressure range (0.7 to 41 kPa) at-8°C. The results of these tests were;

- For scrap steel the friction became stable above 20 kPa.
- For a very rough surface the friction rose between 9 and 32 kPa and then decreased.

Fricton tests were conducted in the laboratory using sample boards; polished, laquered, sanded and papered. The results of the tests were;

- The kinetic friction ranged from .03 to .36, the static friction from .08 to .6.
- The kinetic friction is independant of surface load above 1.3 kPa.
- The static friction is independant of surface load.

TITLE: Experimental study of the Friction of Ice

AUTHOR: Ryvlin, A.Y.

SOURCE: Ice Navigation Qualities of Ships
Kheisin, D.L. Popov, Yu.N. Cold Regions Research and Engineering Laboratory August 1973

ABSTRACT:

A series of full scale experiments were conducted to investigate the Friction Coefficient of ice against a range of materials.

REVIEW AND COMMENTS:

Full scale experiments were conducted saline ice in the arctic at Tiksi Bay. A steel specimen was made in the form of a tank, which could be filled with water, and had a diameter of 0.7 m. The lower surface of the tank approximately represented the roughness of the shell plating of an icebreaker near the waterline. A vibrator was fitted on top of the tank. The maximum weight of the drum was 920 kg, representing 22.5 kPa. The results of the full scale experiments were;

- Over a speed range of 0.2 to 5 m/sec. on wet and dry ice there was essentially no influence on the Friction Coefficient.
- There was no affect on the Friction Coefficient for a specific pressure, related to the total area of the tank base, varying from 9.8 kPa to 22.5 kPa.
- The static Friction Coefficient increased with a decrease in temperature and the dynamic Friction Coefficient was not affected.
- The results of experiments on ice of different roughnesses were;

Place / Month	Air Temperature	State of Ice surface	Friction Coefficient	
			Static	Dynamic
Tiksi, May	0°C	Smooth	0.15	0.06
	0°C	Rough h_b=.5 mm	0.2	0.08
Tiksi, November	-20°C	Smooth	0.32	0.08
	-20°C	Rough h_b=.8 mm	0.39	0.07
Gor'kovskava, March	-8°C	Smooth	0.29	0.07
	-8°C	Rough h_b=1 mm	0.26	0.10

h_b=height of protuberances.

The results indicate that there is no affect on the friction for different ice roughnesses.

- The affect of snow cover was investigated;

Place/ Month	Temperature	State of Ice Surface	Friction Coefficient	
			Static	Dynamic
Tiksi, May	0°C	Rough without Snow	0.16	0.07
	0°C	Fresh Snow, h=0.05 m	0.17	0.08
	-3°C	Fresh Snow, h=0.02 m	0.27	0.14
Tiksi, June	0°C	Fresh snow, h=0.15 m	0.92	0.26
Tiksi, November	-28°C	Rough & Dry No Snow	0.32	0.07
	-2°C	Dense Dry Granular Snow	0.42	0.13

- Water covering the ice surface has no effect on the Friction Coefficient.
- The solidity of the ice or its salinity does not affect the Friction Coefficient.
- The orientation of the ice does not affect the Friction Coefficient.
- The average numerical value of the dynamic Friction Coefficient of ice against ice and the steel against steel is approximatly the same.
- The static Friction Coefficient of ice against ice is twice the Friction Coefficient of ice against steel.
- The average dynamic Friction Coefficient of steel against ice with no snow cover is 0.1.
- Laboratory experiments indicated that the average Friction Coefficient of rusty steel obtained in the laboratory is similar to that obtained at full scale. The Friction Coefficient for polished steel and painted wood was cosiderably less, static = 0.04 Dynamic = 0.02.

TITLE: Friction Measurements of Sea Ice on Flat Plates of Metals, Plastics and Coatings.

AUTHOR: Tusima, K.

SOURCE: Port and Ocean Engineering under Arctic Conditions
POAC 79 ; Norwegian Institute of Technology

ABSTRACT:

Friction tests of cylindrical sea ice specimens on samples of plate at different temperatures, speeds and pressures.

REVIEW AND COMMENTS:

The experimental apparatus consisted of a 0.5 by 0.12 m table moving on rails at a constant speed of .05 m/sec. over the test samples. A cylindrical ice specimen 0.075 m in diameter (44.18 cm^2) is supported by the table and pressed against the test sample over a range of force from 13 to 1000 N (2.94 to 226.3 kPa). The ice samples were taken from Alaska and a salt lake in Japan. The results of the experiments indicated that;

- At -5°C, sliding speed of .1 mm/sec the smooth samples (glass, stainless steel and aluminium) showed small values of friction from 0.01 to 0.03, independant of applied load. The samples of carbon steel and rust proof paint had values ranging from .08 to 0.24 at the higher loads. Inerta 160 had a friction of .14 at the low loads and decreased to a constant .06 at about 500 N (113 kPa)
- Plotting the results as shear stress against normal stress the data shows that shear stress is proportional to normal stress at 2 mm/sec.
- Over a speed range of 2 mm/sec to 3.5×10^{-7} m/sec the Friction Coefficient increases with a decrease in sliding speed.
- Measurements taken with the sample immersed in water were conducted over a range of sliding speeds from 5 to .005 m/sec. and normal force from 13 to 1000 N. The smooth surface of stainless steel gave the lowest value of .015. The Friction Coefficient was shown to decrease with an increase in sliding speed. Submerging the sample had little effect on the friction values.
- The coefficient of friction increases with lowering temperatures.
- Sea ice shows a slightly lower coefficient of friction than sea ice.
- Friction represented as linear function of shear force and normal force.

$$F = AS + A^1P$$

A = contact area
A^1 = 'ploughing' area
P = ploughing strength of ice
F = friction resistance

TITLE: Ice Resistance to Motion of a Ship

AUTHOR: Kashteljan, I. V.
Poznjak, I. I.

SOURCE: Transport Canada Library
#VM 451 K19
1968

ABSTRACT:

An overall review of the engineering and operational factors influencing the operation of a ship in ice.

REVIEW AND COMMENTS:

The report emphasises that the Friction Coefficient is one of the most important factors influencing the performance of an icebreaker in ice, particularly in broken ice. The report notes that ice friction is a self lubricating process due to the melting of the ice caused by the heat generated in the discrete region of actual contact. Slip occurs in the water lubricating layer. The report states that the Friction Coefficient is Coulomb and that the Friction force is independant of velocity and proportional to load.

The numerical values of friction between steel and ice are reported to be between 0.01 to 0.25. Based on full scale measurements the report recommends a dynamic Friction Coefficient between hull and ice of 0.08 to 0.13. This range encompasses all the variables that affect the Friction Coefficient (wetness, velocity, temperature, roughness, etc) except snow, which may cause the coefficient to rise by a factor of 1.5 to 2.

The report emphasises that a scale effect may exist between the model and full scale Friction Coefficient.

TITLE: Low Friction Coatings for Icebreakers

AUTHOR: Calabrese, S.J.;Peterson, M.B.;Ling, F.F.

SOURCE: Department of Transport, United States Coast Guard
Report #CG-D-107-74, Phase I Parts 1 and 2, June 1974

ABSTRACT:

Evaluation of the State of the Art of low friction coatings for Icebreakers. Laboratory tests were conducted on different materials to determine frictional properties. Full scale tests were conducted on two USCG cutters to evaluate two hull surfaces

REVIEW AND COMMENTS:

The laboratory experiments were conducted using small steel samples of material rotated against an ice surface, using a drill press. A number of tests were conducted;

The time of contact between the ice and sample were found to significantly affect the "breakaway" friction, which varied from .55, but was never more than .8. Very low speed or "static" friction remained constant at 0.4. Tests conditions were, Temp. -22°C, Load 90 lbs (40.8 kg), Surface roughness 130 u" CLA (3.3 um CLA), static friction tests speed 0.4"/sec (10 mm/sec). The tests were repeated a number of times and consistant results were obtained.

The effect of load on the Friction Coefficient was determined for 3 surface roughnesses, 240, 130 and 40 u" CLA (6.1, 3.3 and 1.0 um CLA) at -22°C. Loads from 30 to 200 lbs (13.6 kg to 91 kg) were used on an area of 12.4 cm^2 ($1.24 \times 10^{-3} m^2$ 107 - 719 kPa). The Kinetic Friction Coefficient (283 ft/min, 1.44 m/sec) was not appreciably affected by the load and stayed at about 0.1. The "Static" Friction Coefficient (10 mm/sec) for the smooth and medium roughness was not appreciably affected (.2 to .35 for the smooth sample and .45 to .5 for the medium sample) but for the rougher sample increased rapidly from .45 at 30 lbs (13.6 kg) to about .8 at 50 lbs (22.7 kg) and remained about constant above this. The breakaway Friction Coefficient increased for each surface from 30 to 90 lbs (13.6 to 40.8 kg): For the smooth surface from .3 to .45; For the medium surface .55 to .65 and; For the rough surface from .8 to 1.2. Above 90 lbs (40.8 kg) the Friction Coefficient became constant. The increase in Friction Coefficient is attributed to the imbedding of the ice at higher loads and increasing the shear area of the ice.

Roughness was shown to affect each type of friction. At 90 lbs (40.8 kg) the Kinetic Friction increased from about .09 at 40 u" CLA (1.0um CLA)to .11 at 240 u" CLA (6.1 um CLA). Over the same range the static Friction varied from about .28 to .8 and the breakaway Friction from .4 to 1.2.

The effect of temperature was tested for 2 roughnesses with a load of 200 lbs (90.7 kg);

For the smooth sample, 40 u" CLA (1.0 um CLA), the Friction Coefficient reduced slowly from -25 to-7°C. At this point the breakaway dropped from about .5 to .1 and the static friction from about .25 to .1. The dynamic friction remained at about .1. This is considered to be as a result of the significant reduction in shear and adhesion strength of ice above -7°C.

For the rough surface, 130 u" CLA (3.3 um CLA), the Friction Coefficient reduced slowly to about -7°C and then drops to -2°C. At this point the breakaway drops from .55 to .38 and the static drops from .38 to .25. The dynamic Friction Coefficient remains constant at about .1 from -25 to -2 °C. Above about -2°C there is a significant increase in Friction Coefficient for all the modes. This increase is attributed to the large asperities on the steel surface imbedding completely in the the low strength ice. With relative movement between the steel and ice there is no oppurtunity of building up any water film and the asperities continualy shear the ice surface. This is suggested to be the case at full scale with the ice surface interface at about freezing and hull surfaces with greater surface roughness than 130 u" CLA (3.3 um CLA).

The effect of ice surface on the Friction Coefficient was small for the breakaway and static Friction and no effect was recorded for the dynamic Friction Coefficient.

Paint coatings of different hardness but similar roughness were tested. All the surfaces were similar up to about -10°C when they became different. The hard surface showed the anticipated reduction in Friction Coefficient but the soft surface showed an increase. This is attributed to the deformation of the surface under the load which acted like an increase in roughness.

Full scale tests were conducted on two USCG cutters to evaluate two hull coatings, the polyurethane elastomer and the non-elastic polyurethane. The non-elastic polyurethane produced a better bond to the primer.

Recommendations were made to tests a series of materials to investigate the affect of material properties.

TITLE: Low Friction Coatings for Icebreakers - Phase II Part I and II Laboratory and Field Tests

AUTHOR: Calabrese, S.J., Peterson, M.B.
Ling, F.F.

SOURCE: Department of Transport United States Coast Guard
Report Number CG-D-32-76, February 1976

ABSTRACT:

In Part I, simulation tests are conducted to determine the effect of velocity, humidity, temperature, coating thickness and contact area on the coefficient of friction between ice and a ship's hull. From the results the friction resistance of the hull of an icebreaker are theorised.
In part II, a full scale evaluation of the coatings is made on small icebreakers.

REVIEW AND COMMENTS:

In previous work the Friction Coefficient had been shown to increase with roughness for all the materials tested. Low Friction results when harder materials are used. With softer materials the ice penetrated the surface and caused a higher Friction Coefficient. With softer, rough surfaces the Friction Coefficient was lower due to the material unable to penetrate the ice. In summary it was difficult to separate the effect of surface roughness and hardness on Friction.

The coefficient of Friction of materials sliding against ice at low temperatures (-18^{o}C) reduces with the velocity at low speeds and then will level off and remain constant. The speed at which the Friction levels off, is dependant on the surface roughness and type of material. For smooth steel 100 u" CLA (2.5 um CLA) the drop is fast and occurs at about .2 m/sec, for rougher steel the reduction is slower and occurs over a range from 0 to .7 m/sec. The values start at the static value and gradually decrease to the kinetic value as the speed increases. The same trend is observed using surfaces coated with various plastics.

The Coefficient of Friction does not appear to change with the ice roughness. The only change is noted at very low speeds.

The low speeds (<.45 m/sec) Friction Coefficient varies significantly with the humidity but at higher speeds (>.45 m/sec) there is little apparent affect. This is attributed to the film of moisture that forms on the ice sample. At higher speeds the Frictional heat provides water at the ice surface and less effect of moisture is noted.

The effect of contact area was analysed using three different samples; 2, 1.5 and 1.3 in^2 (12.9, 9.7 and 8.4 cm^2),at -20°C and using a sample roughnes of 130 u" CLA (3.3 um CLA). For each contact area the Friction was found to be constant up to about 100 lbs (45.4 kg) and then reduces. Plotting coefficient of Friction against the reciprical of pressure demonstrates that the data falls on a straight line up to about 90 1/psi (13 1/kPa) and then tends to reduce. This is attributed to the changing area of contact between the ice sample and material. If;

$$f = \frac{A.S}{L}$$

f = 1/coefficient of friction
S = Shear strength of ice
L = Load
A = Real area of contact

Then, as the load increases, the two surfaces will be pushed further together and the real area of contact (A) will increase to a limiting value defined by the dimensions of the sample. Providing the shear strength of the ice (S) remains constant this will result in an increase in "f", the reciprical of the Friction Coefficient. At the shear yield strength of the material "S" will fall and so will "f". Two Regimes of Friction Coefficient are defined, one above 100 psi (690 kPa) Regime I, and one below, Regime II. In Regime I the Friction Coefficient is independant of pressure and in Regime II the Friction Coefficient reduces with pressure.

Additional tests were performed on two larger surfaces on a sled dragged across an indoor ice rink. Two runners 3" by 36" (.076 by 0.914 m) and a 28" by 44" (0.711 by 1.12 m) flat plate with loads from 210 lbs to 5,410 lbs (95 to 2,456 kg) and suface roughness of 310 to 400 u" CLA (7.87 to 10.2 um CLA) at an ice temperature of -9°C and air temperature of +7°C.

The Friction Coefficient of the runners with with 2,456 kg load - 173 kPa was approximately 0.44 breakaway and 0.22 to 0.1 dynamic. The large flat plate resulted in an increase in both breakaway and dynamic friction. The dynamic friction ranged from .72 to 0.1 and the test exhibited severe stick-slip during the run.

In summary the coefficient of Friction depends on the pressure of contact. Larger areas (smaller pressures) have lower Friction Coefficients than smaller areas (higher pessure) with the same load.

Similar tests in a model tank produced different results for a 1:10 model of the larger tests. No Friction effect was seen between the runners and the sled nor with the different loads. This difference is considered to be the result of the softer ice being used in the model basin.

No effect on the thickness of the coating material was identified.

A model for the ice/material interface is proposed that incorporates the results of the model experiments.

TITLE: Low Friction Coatings for Icebreakers

AUTHOR: Calabrese, S.J., Ling, F.F.

SOURCE: Report to US Coast Guard #CG-D-69-78, October 1978

ABSTRACT:

Phase III is a continuation of Phases I and II in which non solvent coatings gave the best protection for icebreaker hulls. This part documents the reduction in resistance, fouling characteristics and cost benifits. Phase III also investigates the areas of highest abrasion and Friction by using water resistance low bonding strength coatings on icebreaker models.

REVIEW AND COMMENTS:

The full scale tests indicated that a reduction in Resistance could be achieved by applying a low a Friction coating. The model tests were conducted in three phases to examine the; a) Abrasion; b) Frictional Resistance on specific hull parts; and c) an optimum distribution of a 10% and 20% smooth hull coating was investigated.

The results of the model test programm are;

1. Certain areas of the hull contribute more to the resistance of a ship than others.
2. Less coating is necessary at low ice thickness to obtain the same reduction in resistance as obtained at high thickness.
3. From the friction tests on a plank, there was no difference between the hull ice friction factor obtained from tests of the top surface in the submerged, flushed wet, or dry (direct from the model basin), unlubricated condition. Tests of the edge gave same results as top surface ice at low speeds.
4. The effect of speed on hull ice friction factor is small although it may become significant at high speeds of 15 knots.
5. Friction correlates with roughness although different friction results from surfaces with the same roughness.

TITLE: Field Tests of the Kinetic Friction Coefficient of Sea Ice

AUTHOR: Tatinclaux, J. C.
Murdey, D.

SOURCE: US Army Cold Regions Research and Engineering Laboratory
Report #CRREL 85-17

ABSTRACT:

Report presents the results of the Friction Coefficient tests conducted on board the POLARSTERN during the 1984 trials off the coast of Labrador. The tests used Inerta 160 coated steel plates and bare steel plates and examined the effects of ice crystal orientation, normal force and sample speed.

REVIEW AND COMMENTS:

Four materials were tested;

Inerta Coated Steel - roughness = 0.97 $\pm$ 0.34 um CLA
Roughened Intera Steel = 39 $\pm$ 0.8 um CLA
Rough Bare Steel = 1.1 $\pm$ 0.2 um CLA
Sand Blasted Steel = 7.1 $\pm$ 0.7 um CLA

The results from the test programme may be summarised as;

a) Columna and Granula Sea Ice showed no significant differences in Friction Coefficient.

b) Effect of wear on sample; A series of tests to examine the effect of repeated tests on the same ice sample. A smooth and rough Inerta coated surface was used with a 0.3m square sample at a test speed of 10-12 cm/sec and normal force of 804-824 N (9 kPa) on wet and dry ice. Temperature was about -1 to -8 °C. The results indicated that over a series of 10 tests the Friction Coefficient was not affected and equivalent values were recorded during the first and last runs.

c) Effect of Normal Pressure; Normal pressure was tested at 14-18 kPa and 7-10 kPa for a 0.3m square sample on roughened Inerta coated steel, Temperature was about -1°C, sample speed was 3 to 30 cm/sec, on dry ice. The results of the tests showed no affect of pressure on the Friction Coefficient over the range tested.

d) Effect of Velocity, Crystal Orientation and Surface Conditions; For smooth dry Inerta coated steel, normal pressure 9kPa, there was no effect on Friction Coefficient for a speed range of 3 to 30 cm/sec. On roughened Inerta coated steel and bare steel the Friction Coefficient

initially decreased rapidly with increased speed from about .12 to .05. The scatter for the samplles increased with surface roughness and when the sample is wetted. The Friction Coefficient increased with surface roughness but depended on the surface morphology and type of surface. Water repelent surfaces such as Inerta had lower Friction Coefficients than wetting surfaces such as bare steel.

The full scale measurement were compared to tests on the same samples conducted in the laboratory. The results of the comparison are;

Material Surface	Laboratory Tests	Full Scale Tests	
		Dry surface	Wet Surface
Inerta 160 RA=1um	.029	.029	.034
Steel RA=1.1um	.192	.058	.083
Steel RA=7.1um	.197	.082	.214

The correlation appears resonable between the Laboratory tests and the full scale wet sample tests. It may be noted thsat the Laboratory tests were conducted with dry samples although melting took place during the test.

TITLE: Model Tests on Ice Rubble Size and Ship Resistance in Ice Rubble

AUTHOR: Ettema, R.

SOURCE: Cold Region Science and Technology, Vol 12(1986), 229-243

ABSTRACT:

Model tests on a 3 m long model fitted with two bows were conducted in Urea ice at the IIHR ice tank. The model was constructed to permit the measurement of forces excerted between the midbody and bow sections. The test examined the effect of ice rubble size, ship speed and the Frictional resistance of the midbody section

REVIEW AND COMMENTS:

The tests resulted in the following conclusions;

a) The resistance encountered by the test hull increased with increasing rubble piece size and with speed.

b) The test hull encountered a higher resistance moving through a mush ice cover than an equally thick layer of rubble ice. The tests consisting of a mix between the rubble and mush ice exhibited an intermediate resistance.

c) The proportion of ice rubble resistance to total resistance encountered by the hull decreased with increasing speed because the open water resistance increased faster than the ice rubble resistance.

d) The Frictional resistance of the hull midbody was dependant on speed size of ice rubble and thickness of ice cover.

TITLE: Coefficient of Friction Between Ice and Some Construction Materials, Plastics and Coatings

AUTHOR: Oksanen, P.

SOURCE: Technical Research Centre of Finland, Laboratory of structural Engineering, Report #7, April 1980

ABSTRACT:

A theoretical and experimental study was conducted to evaluate the Friction Coefficient between ice a some other materials. The analytical work was based on the assumption that the friction is caused by the water layer between the ice and the material. The laboratory experiments were conducted with a material sample rotating on a circular bed of ice.

REVIEW AND COMMENTS:

The results of the laboratory experiments may be summarised as;

a) The experiments were conducted with a range of different samples 115cm^2 with a normal load of 10 to 50N (.87-4.3 kPa), air temperature 0 to -15 ^{o}C and sample speed of 0.5 to 3 m/sec.

b) The Friction Coefficient decreased with normal load for all sample materials tested.

c) The Friction Coefficient at low temperature was linear decreased with temperature, to about -5^{o}C. Above this temperature the Friction Coefficient started to increase.

d) The effect of sample speed on the Friction Coefficient varied as a function of temperature. At low temperatures the Friction Coefficient reduces with speed, at about -5^{o}C the Friction Coefficient tended to be independant of speed and at -1^{o}C the Friction Coefficient increased with speed.

e) The effect of wetting the ice prior to the test resulted in a larger scatter of the data. The Friction Coefficient of wet ice was dependant on normal load in a similar way to the dry ice, decreasing with normal load. The speed effect with wet ice was not clear but tended to increase with increase speed, particularly for the rougher surfaces. The Coefficient of Friction for wet ice is approximately five times higher for wet ice than dry ice at -1^{o}C.

TITLE: Ice Trials to Evaluate Low Friction Coatings on the CCGS LOUIS S ST LAURENT

AUTHOR: Arctec Canada Ltd

SOURCE: Arctec Canada Report to Canadian Coast Guard Fleet Systems Report #FR357C-5, November 1979

ABSTRACT:

Ice trials were conducted in Admiralty Inlet and Strathcona Sound in July in .75-1.75 m deteriorated ice. Estimates are made on the performance of the LOUIS S STLAURENT with an Inerta Coating.

REVIEW AND COMMENTS:

A rotating ice friction device was used to measure the hull surface Friction Coefficient. Surface roughness was also recorded together with laboratory tests on similar materials. The results of the full scale tests yielded higher Friction Coefficients than the laboratory tests. The full scale tests did not appear to be dependent on speed, although the laboratory experiments did. The difference in correlation between the laboratory and field trials was attributed to the temperature difference between the two experiments, $-10^{o}C$ for the laboratory tests and -1 to $+2^{o}C$ in the field.

TITLE: Test Report on Friction Tests
Conducted on the Ice Tribometer

AUTHOR: Arctec Canada Ltd

SOURCE: Transport Canada R&D Centre
Report # TR 332C-2, 1978

ABSTRACT:

Tests were conducted in the laboratory on a swinging arm friction measuring device.

REVIEW AND COMMENTS:

The results of the tests are summarised as;
The effect of sliding speed on the Friction Coefficient is significant.
The effect of ice salinity is more evident for bare steel plates and less for smooth surfaces.
Tests show that low friction materials produce Friction Coefficients of about 0.05.
Static Friction Coefficient does not appear to be affected by ice salinity.
Surface roughness does not appear to affect the Friction Coefficient.

TITLE: The Friction and Creep of Polycrysalline Ice

AUTHOR: Barnes, P.
Tabor, D.

SOURCE: Proceedings of the Royal Society, London, A. 324, 127-155 (1971)

ABSTRACT:

A series of experiments are conducted on a cone of ice sliding over a range of material. The tests are over a speed range of 10^{-8} to 10^{-1} m/sec. The materials used are Granite, Glass, Brass and Steel.

REVIEW AND COMMENTS:

The results of the tests indicated that under conditions of strong interfacial adhesion the friction is due to the shearing of a thin layer of ice close to the interface. At speeds above 1 mm/sec frictional heating is sufficient to cause appreciable surface melting and the friction can fall to very low values.

TITLE: The Kinetic Friction of Ice

AUTHOR: Evans, D.C.B.
Nye, J.F. Cheeseman, K.J.

SOURCE: Proceedings of the Royal Society, London,
A. 347, 493-512 (1976)

ABSTRACT:

Friction experiments were conducted using a pendulum sliding on a revolving drum of ice. The experiment was intended to simulate the interface between an ice skate and ice.

REVIEW AND COMMENTS:

TITLE: SS MANHATTAN Arctic Marine Project.
Ice Breaking Model Tests at Helsinki Ice Model Basin for Arctic Tanker Design Project

AUTHOR: Arctec Incorporated

SOURCE: Report #314, for the Department of Commerce
December 1970

ABSTRACT:

Ice model testing activities associated with the Arctic Tanker project are summarised in order to described. Model ship correlation, results of the resistance tests and the results of the manoeuvring tests are summarised. Conclusions are drawn where possible and recommendations for future work.

REVIEW AND COMMENTS:

Models of the MANHATTAN and the VLADIVOSTOK where tested in ice in conjunction with length, beam, flare angle, Friction Coefficient and bow form variations. The variation of friction was achieved by covering different parts of the model hull with emory paper. The main result of the friction tests with the emory paper covered model was an 80% increase of resistance over the forebody and 20% on the sides. The report postulates that since the rough hull appears to be responsible for about 50% of the total resistance, forebody ice friction is responsible for more than 40% and the midbody contributes more than 10%.

TITLE: Computer Simulations of the Behavior of Maritime Structures

AUTHOR: Hooft, J.P.

SOURCE: Marine Technology, Volume 23 No. 2, April 1986. pp 139 - 157.

ABSTRACT:

REVIEW AND COMMENTS:

The paper discusses the calculation models for the creation of time domain computer simulations. Most time domain simulations consist of a continuous evaluation of the velocity components of a body. These are obtained by a specific integration of the accelerations which are derived from Newtons low.

$$f = m.a.$$

f = Momentary excitation force generated by external phenominum
m = Mass matrix
a = Momentary acceleration

The continual determination of the acceleration is the quintessence of the simulation.

For the application of the simulation process, it is possible to use various mehtods to describe the relationships between the influencing factors and resultant forces.

Most often, analytical formulations are chosen based on their resultant calculations corresponding to existing data.

Once the formulations are selected, the coefficients are determined by regression analysis.

It should be noted that the models do not necessarily represent the physical relation, no the coefficients on physical properties. Also, the values derived are partly artificial and cannot be used outside the range for which physical testing has been derived.

Selection of formulations is important. Since in reality any one variable will be influenced, to a greater or lesser extent, by many other variables,

it is not always clear whether a particular interaction has a primary or secondary influence on another. ie. The roll angle is affected by both roll angle and wave action. But is the interaction a wave dependent part of the rolling motion or a roll dependent part of the wave excitation.

The two extreme ways of generating the simulation are;

1. Solving the complete environmental dynamics of a structure, as a function of external forces, at each moment of time.

   This procedure requires significant computer power to complete the calculations and maintain real time, continuous simualtion.

2. Advanced solution of all resultant forces as a function of all possible environmental conditions. During the simulation these are used and interpolation procedures are used to define the dynamics. This procedure requires large data storage capacity.

For engineering purposes a simpler and more efficient method is used. In this proceedure, use is made of empirical knowledge of the flow around the structure and its effects on the excitation forces.

There are many forms of this procedure, but they all rely on the determination of these forces prior to real time simulation.

Mathematical description should consider hydrodynamic interactions of one part of the structure on another, eg. flow variations in propeller due to bilge vartex, etc.

Time dependent functions should be considered, these are influencing factors that change in time such as variations in a force as a function of the motion preceeding the considered point in time. These may be called "memory effects" and examples are surfaces moving near a fixed wall, damping forces, impulse forces, etc.

Descriptions of formulations are given and references provided for a range of specific interations.

APPENDIX 2

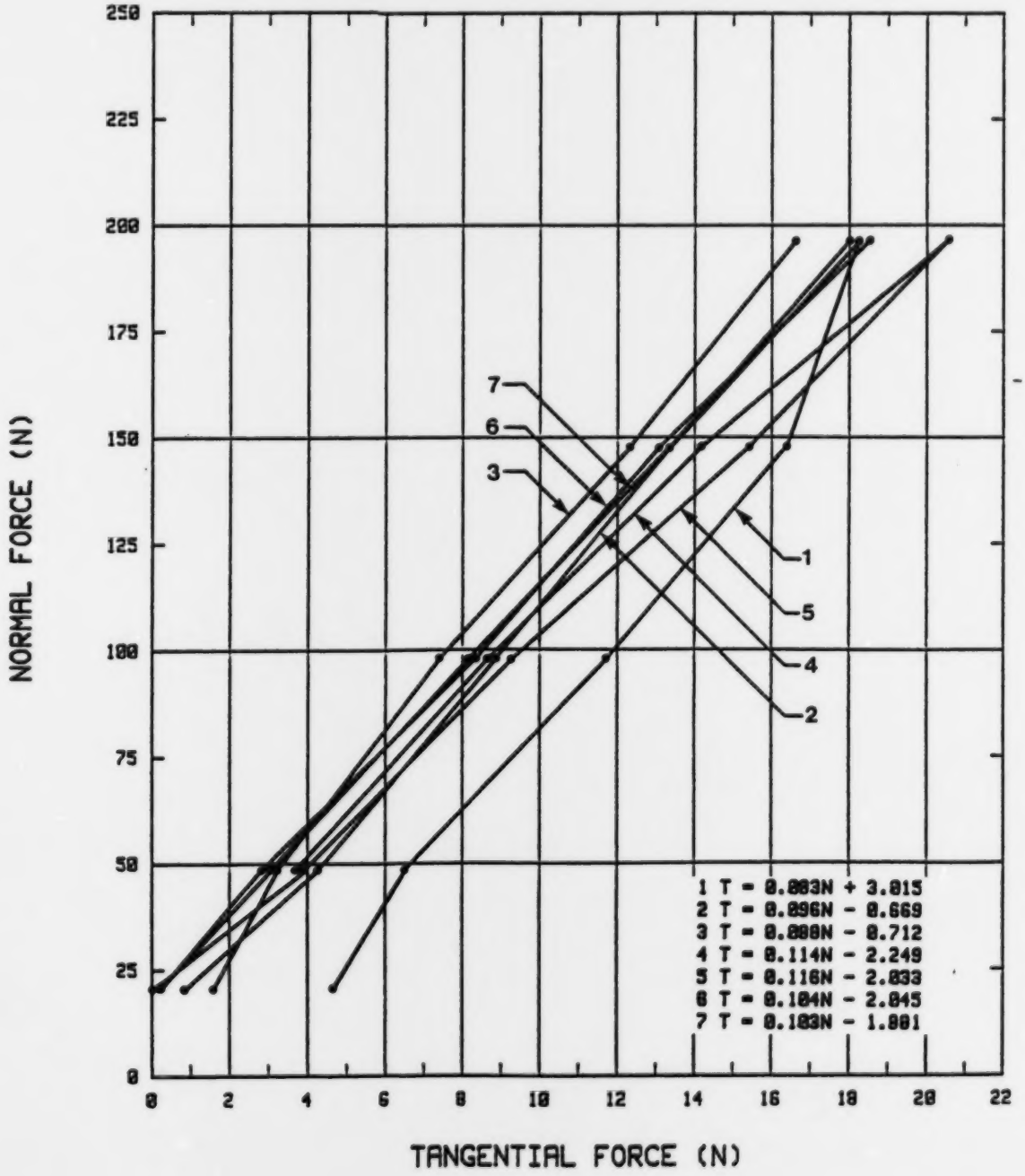
SURFACE DEFINITION TEST RESULTS

DESCRIPTION: ARCTIC Stern; Nominal Friction Coefficient = 0.1

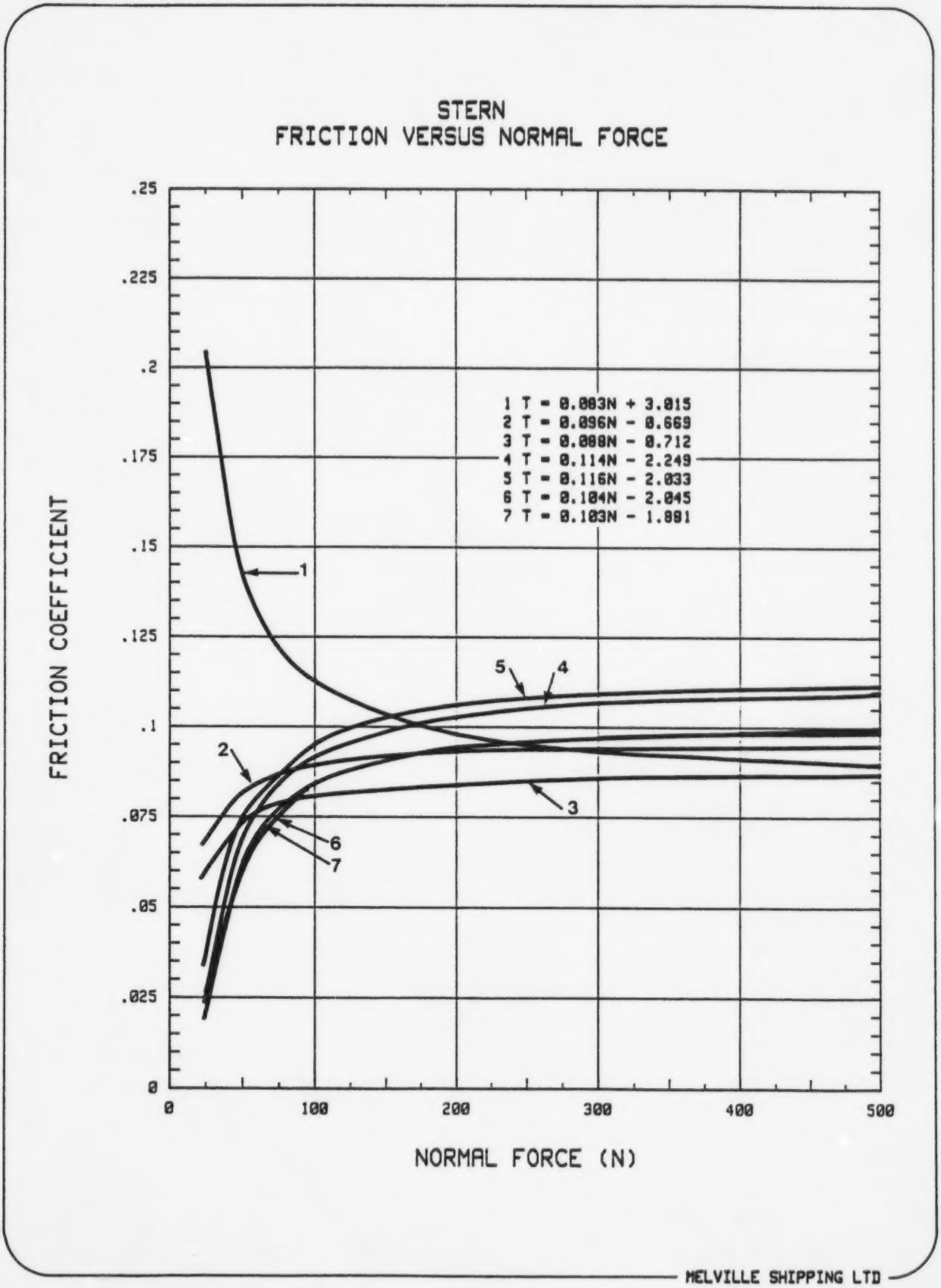
	Date	Normal Load (N)	Tangential Load (N)	Friction Coefficient	Normal, Tangential Force Relationship
1.	23-12-86	19.6	4.74	0.242	
		49.0	6.47	0.132	
		98.1	11.77	0.120	
		147.2	16.34	0.111	
		196.2	18.25	0.093	T = 0.083N + 3.015
2.	21-01-87	19.6	0.96	0.049	
		49.0	4.21	0.086	
		98.1	8.93	0.091	
		147.2	13.40	0.091	
		196.2	18.05	0.092	T = 0.096N - 0.669
3.	21-01-87	19.6	1.55	0.079	
		49.0	3.19	0.065	
		98.1	7.46	0.076	
		147.2	12.36	0.084	
		196.2	16.68	0.085	T = 0.088N - 0.712
4.	30-01-87	49.0	3.68	0.075	
		98.1	8.73	0.089	
		147.2	14.13	0.096	
		196.2	20.60	0.105	T = 0.114N - 2.249
5.	13-02-87	19.6	0.04	0.002	
		49.0	3.92	0.080	
		98.1	9.23	0.094	
		147.2	15.46	0.105	
		196.2	20.06	0.105	T = 0.116N - 2.033
6.	06-02-87	19.6	0.16	0.008	
		49.0	2.79	0.057	
		98.1	8.34	0.085	
		147.2	13.25	0.090	
		196.2	18.44	0.094	T = 0.104N - 2.045
7.	06-02-87	19.6	0.16	0.008	
		49.0	3.09	0.063	
		98.1	8.24	0.084	
		147.2	13.40	0.091	
		196.2	18.25	0.093	T = 0.103N - 1.881

AVERAGE FRICTION COEFFICIENT = 0.101; STANDARD DEVIATION = 0.0116

STERN
TEST PANEL RESULTS



MELVILLE SHIPPING LTD

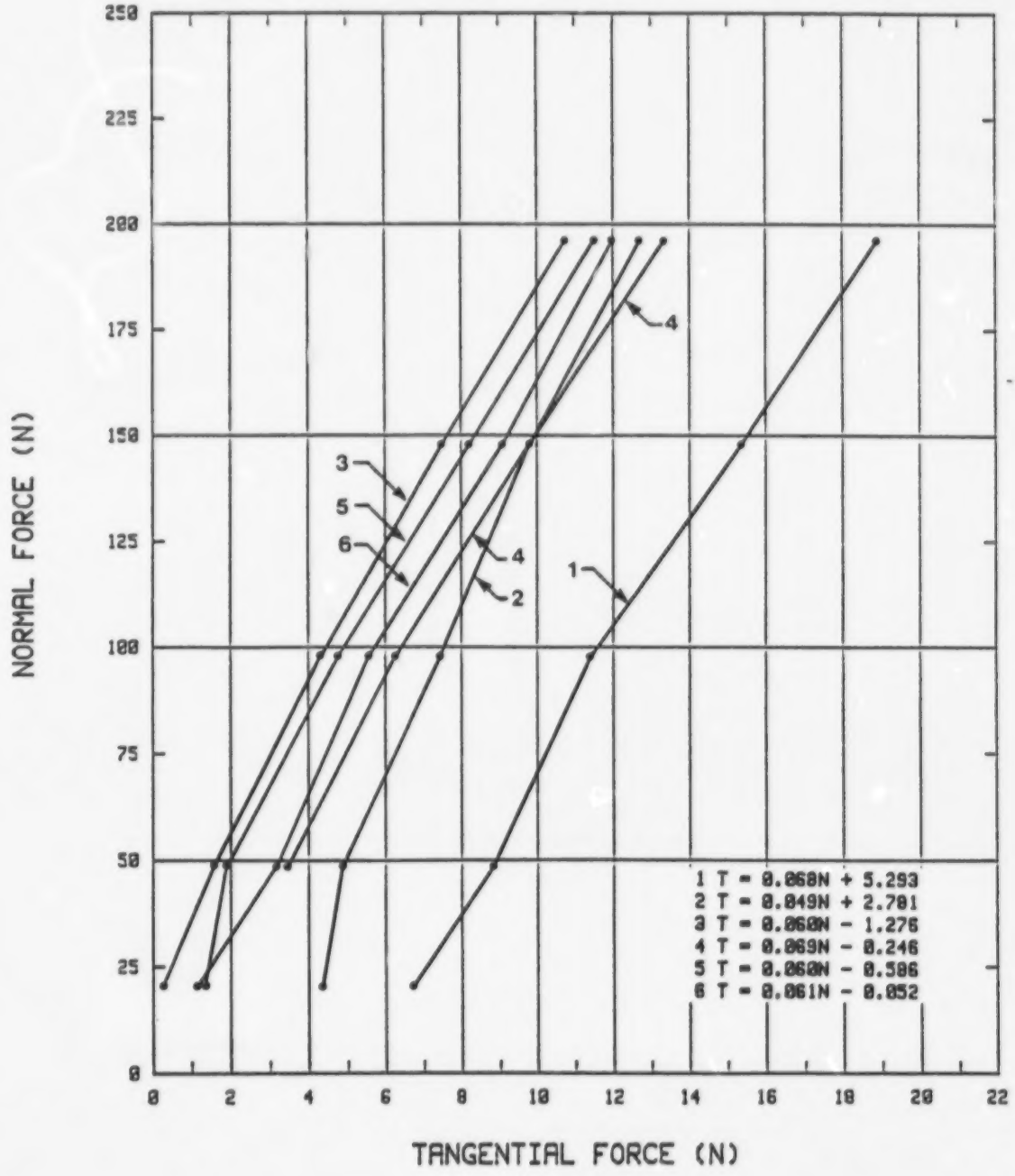

STERN
FRICTION VERSUS NORMAL FORCE
1 T = 0.003N + 3.015
2 T = 0.096N - 0.669
3 T = 0.088N - 0.712
4 T = 0.114N - 2.249
5 T = 0.116N - 2.033
6 T = 0.104N - 2.045
7 T = 0.103N - 1.881
FRICTION COEFFICIENT
.25
.225
.2
.175
.15
.125
.1
.075
.05
.025
0
0
100
200
300
400
500
NORMAL FORCE (N)
MELVILLE SHIPPING LTD

DESCRIPTION: Surface 1; Middle Surface Friction Coefficient = 0.061

	Date	Normal Load (N)	Tangential Load (N)	Friction Coefficient	Normal, Tangential Force Relationship
1.	23-12-86	19.6	6.74	0.344	
		49.0	8.87	0.181	
		98.1	11.38	0.116	
		147.2	15.31	0.104	
		196.2	18.84	0.096	T = 0.068N + 5.293
2.	21-01-87	19.6	4.19	0.214	
		49.0	4.85	0.099	
		98.1	7.46	0.076	
		147.2	9.86	0.067	
		196.2	12.75	0.055	T = 0.049N + 2.781
3.	21-01-87	19.6	0.24	0.012	
		49.0	1.57	0.032	
		98.1	4.22	0.043	
		147.2	7.51	0.051	
		196.2	10.79	0.055	T = 0.06N - 1.276
4.	30-01-87	49.0	3.33	0.068	
		98.1	6.18	0.063	
		147.2	9.86	0.067	
		196.2	13.34	0.068	T = 0.069N - 0.246
5.	03-02-87	19.6	1.33	0.068	
		49.0	1.88	0.018	
		98.1	4.71	0.048	
		147.2	8.10	0.055	
		196.2	11.58	0.059	T = 0.06N - 0.586
6.	06-02-87	19.6	1.14	0.058	
		49.0	3.09	0.063	
		98.1	5.69	0.058	
		147.2	8.98	0.061	
		196.2	11.97	0.061	T = 0.061N - 0.052

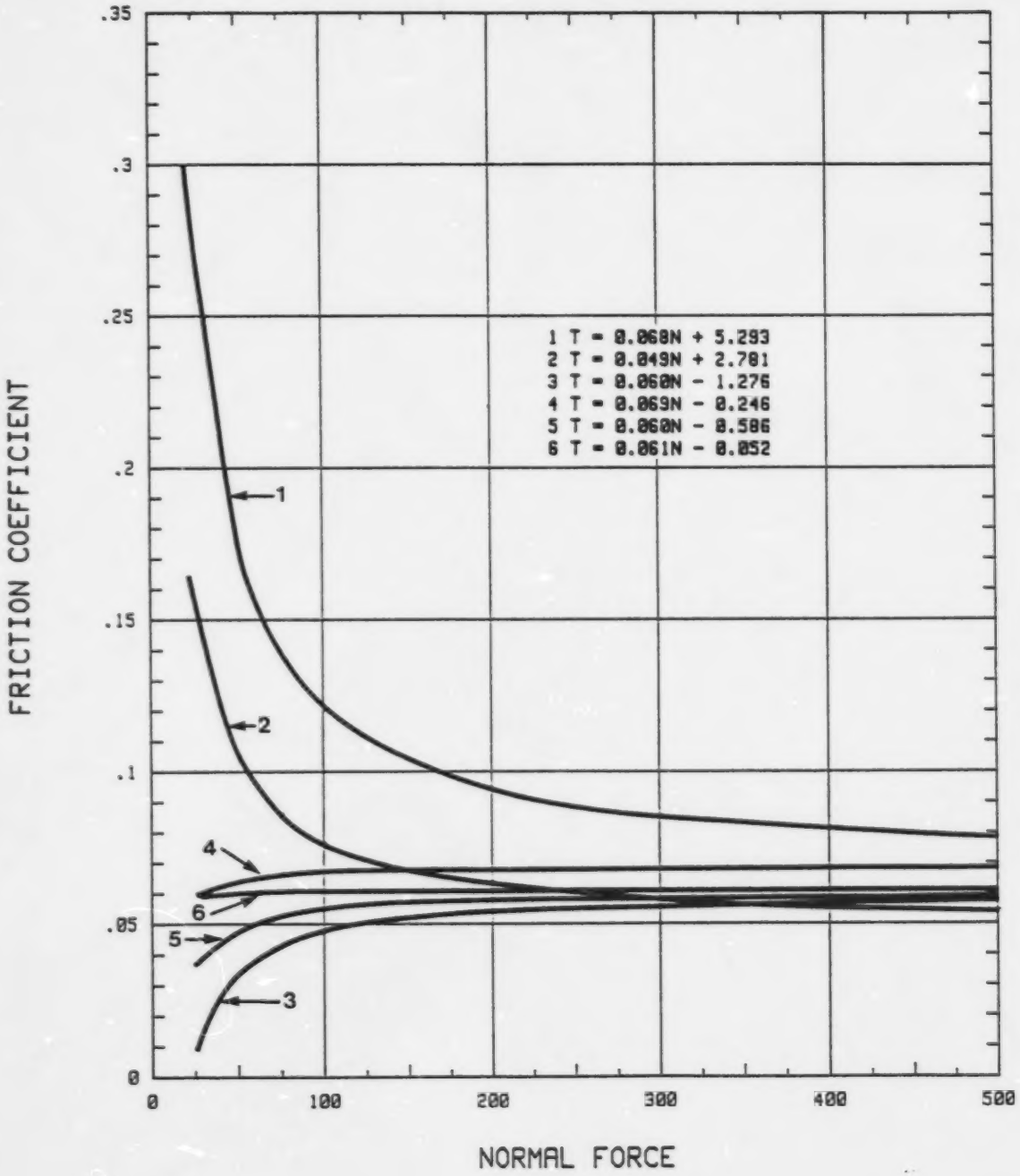
AVERAGE FRICTION COEFFICIENT = 0.061; STANDARD DEVIATION = 0.0072

SURFACE - 1
TEST PANEL RESULTS



MELVILLE SHIPPING LTD

SURFACE - 1
FRICTION VERSUS NORMAL FORCE



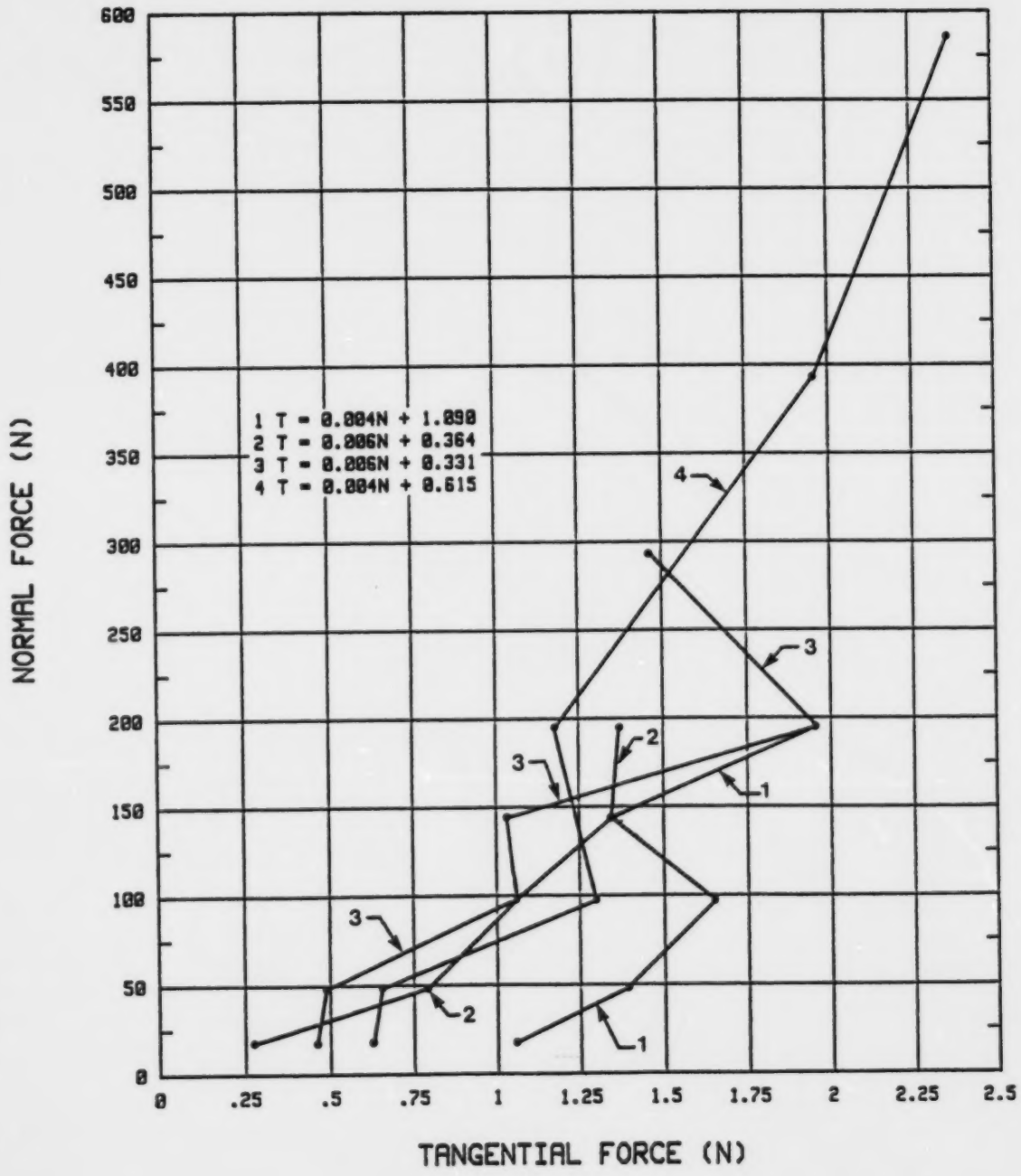
MELVILLE SHIPPING LTD

DESCRIPTION: Surface 2; Smooth Surface Friction Coefficient = 0.005

	Date	Normal Load (N)	Tangential Load (N)	Friction Coefficient	Normal, Tangential Force Relationship
1.	06-03-87	19.6	1.06	0.054	
		49.0	1.37	0.028	
		98.1	1.67	0.017	
		147.2	1.32	0.009	
		196.2	1.96	0.010	T = 0.004N + 1.090
2.	06-03-87	19.6	0.27	0.014	
		49.0	0.78	0.016	
		98.1	1.08	0.011	
		147.2	1.32	0.009	
		196.2	1.37	0.007	T = 0.006N + 0.364
3.	06-03-87	19.6	0.47	0.024	
		49.0	0.49	0.010	
		98.1	1.08	0.011	
		147.2	1.03	0.007	
		196.2	1.96	0.010	
		294.2	1.47	0.005	T = 0.006N + 0.331
4.	09-03-87	19.6	0.67	0.034	
		49.0	0.69	0.014	
		98.1	1.28	0.013	
		196.2	1.18	0.006	
		392.4	1.96	0.005	
		588.6	2.35	0.004	T = 0.004N + 0.615

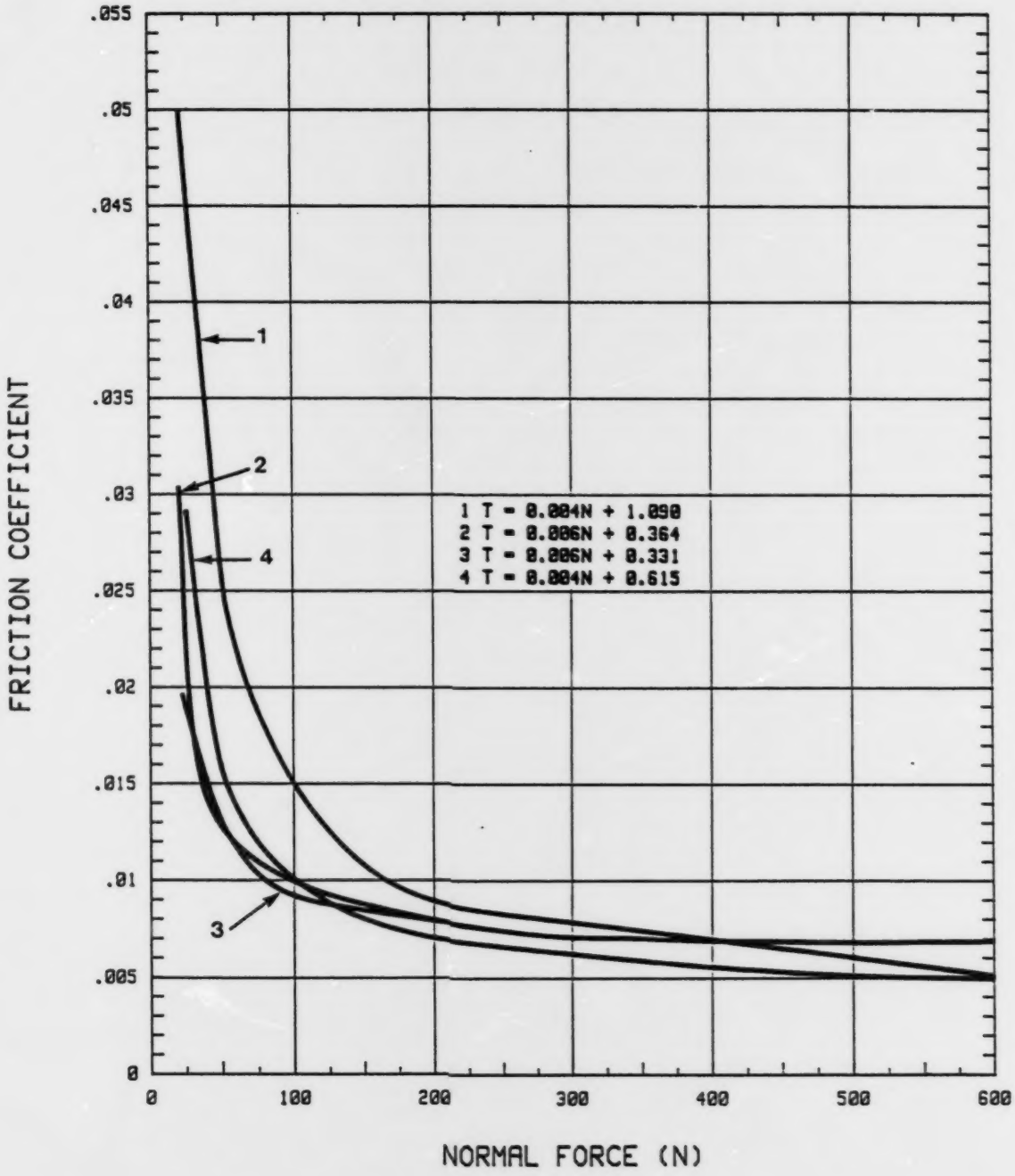
AVERAGE FRICTION COEFFICIENT = 0.005; STANDARD DEVIATION = 0.0012

SURFACE - 2
TEST PANEL RESULTS



MELVILLE SHIPPING LTD

SURFACE - 2
FRICTION VERSUS NORMAL FORCE



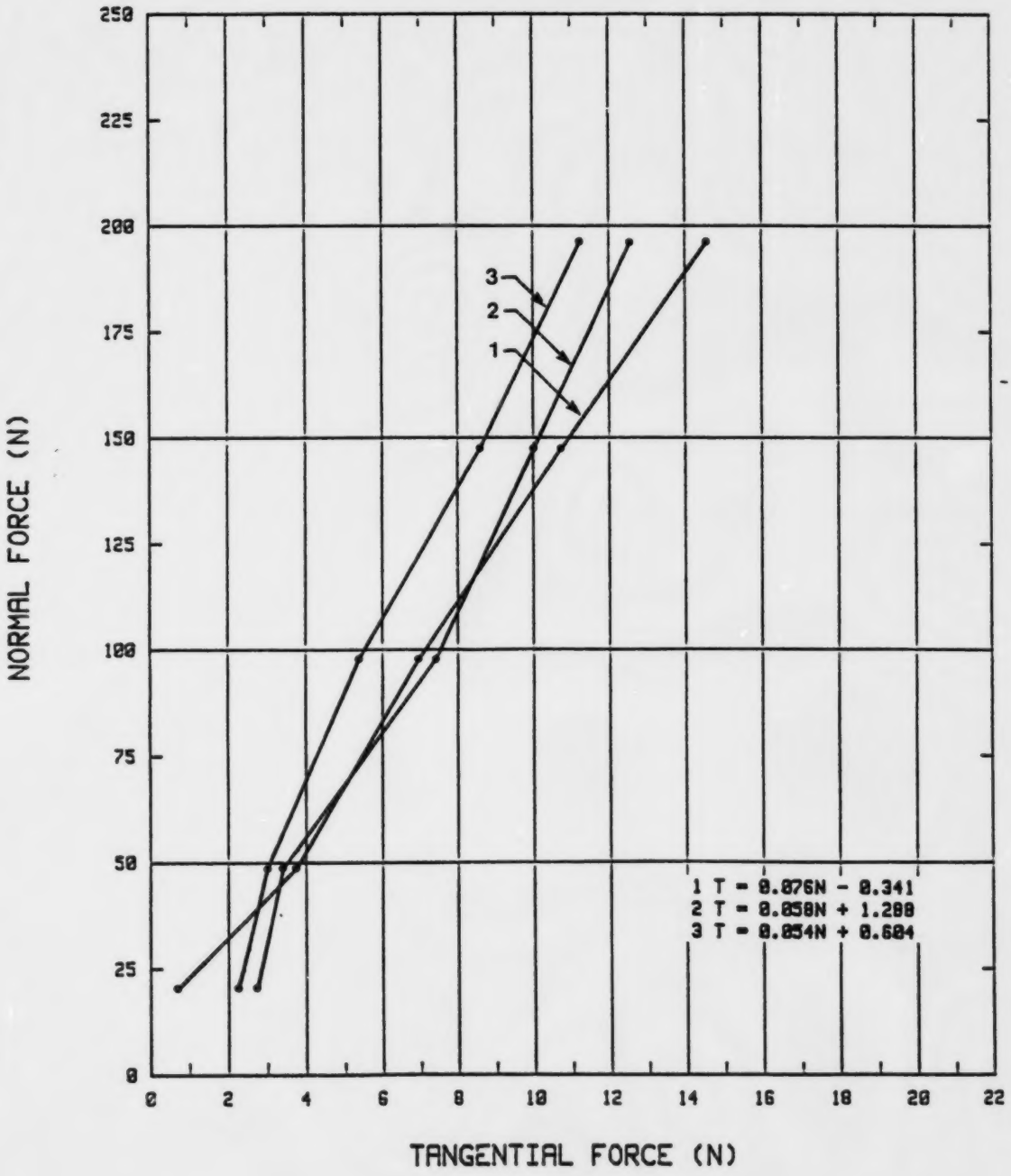
MELVILLE SHIPPING LTD

DESCRIPTION: Surface 3; First Rough Surface Friction Coefficient = 0.067

	Date	Normal Load (N)	Tangential Load (N)	Friction Coefficient	Normal, Tangential Force Relationship
1.	03-02-87	19.6	0.88	0.045	
		49.0	3.77	0.077	
		98.1	6.97	0.071	
		147.2	10.75	0.073	
		196.2	14.52	0.074	T = 0.076N - 0.341
2.	06-02-87	19.6	2.78	0.142	
		49.0	3.43	0.070	
		98.1	7.36	0.075	
		147.2	10.01	0.068	
		196.2	12.56	0.064	T = 0.058N + 1.288
3.	06-02-87	19.6	2.12	0.108	
		49.0	2.99	0.061	
		98.1	5.40	0.055	
		147.2	8.54	0.058	
		196.2	11.38	0.058	T = 0.054N + 0.604
4.	10-02-87	98.1	1.57	0.016	
		147.2	4.86	0.033	
		196.2	8.04	0.041	T = 0.072N - 5.314
5.	03-02-87	98.1	1.28	0.013	
		147.2	4.27	0.029	
		196.2	8.44	0.043	T = 0.073N - 6.077

AVERAGE FRICTION COEFFICIENT = 0.067

SURFACE - 3
TEST PANEL RESULTS



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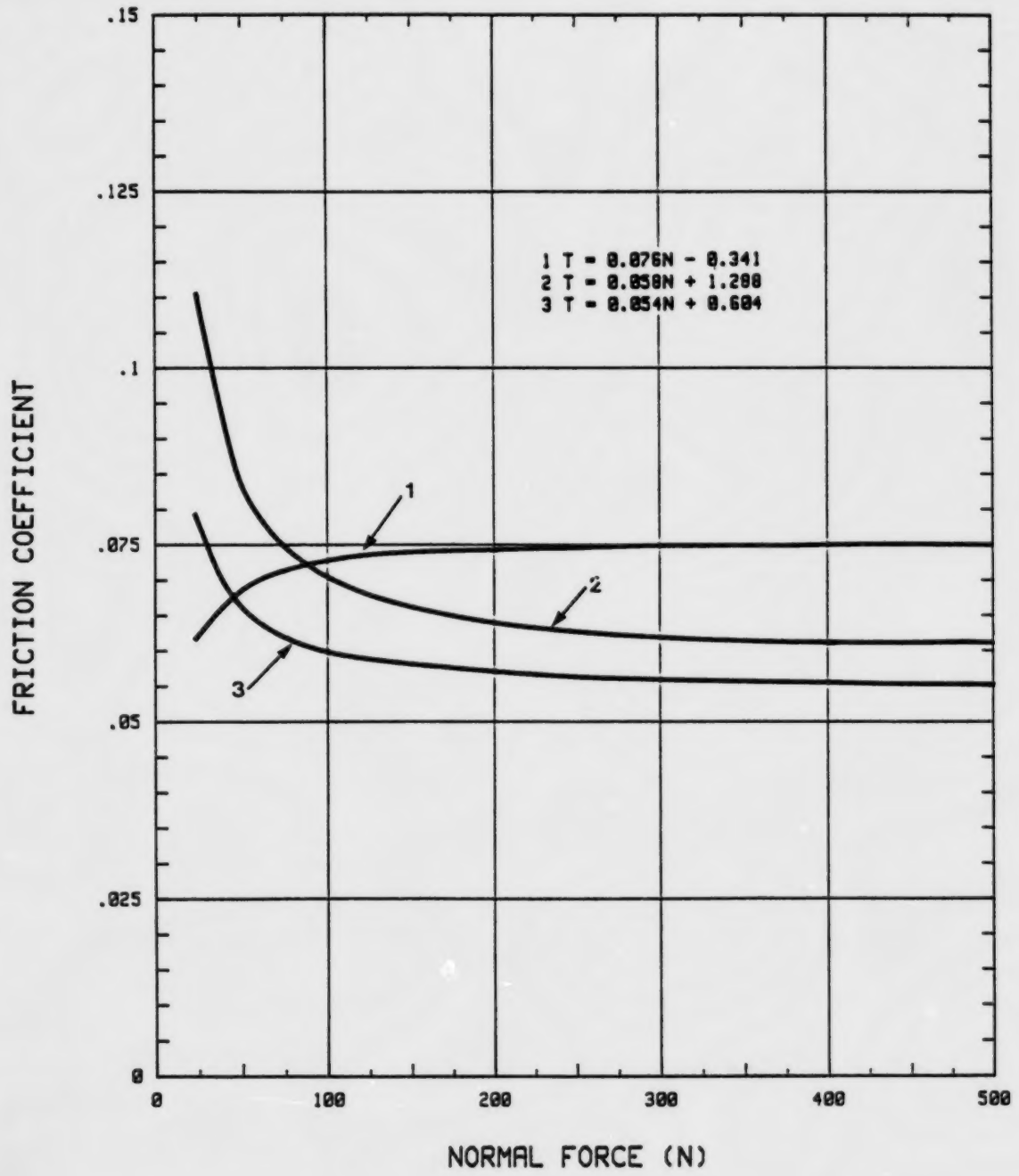
SURFACE - 3
FRICTION VERSUS NORMAL FORCE



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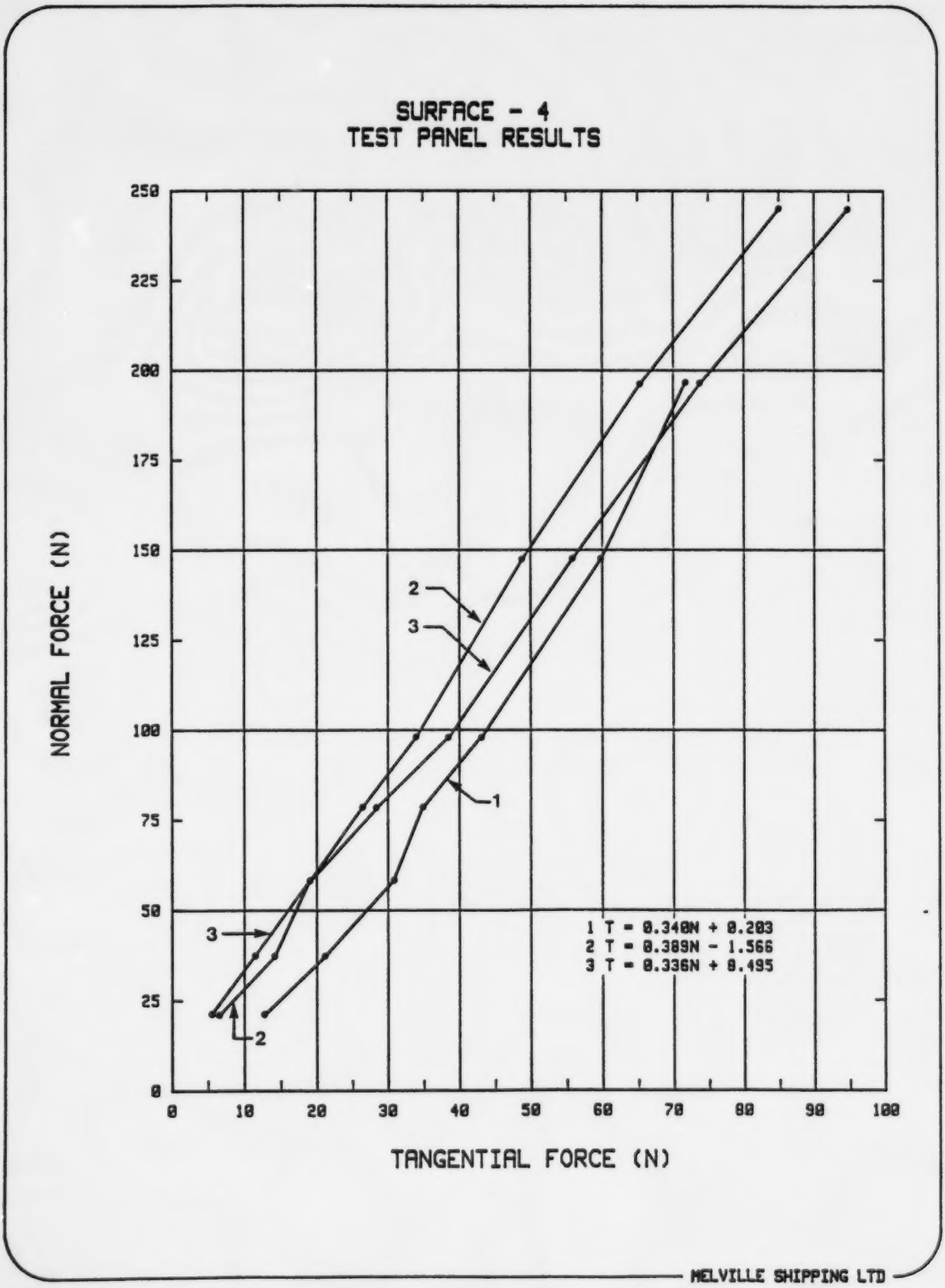
DESCRIPTION: Surface 4; Rough Surface Friction Coefficient = 0.355

	Date	Normal Load (N)	Tangential Load (N)	Friction Coefficient	Normal, Tangential Force Relationship
1.	06-10-87	19.6	12.65	0.645	
		39.2	20.95	0.534	
		58.9	30.08	0.511	
		78.5	35.06	0.447	
		98.1	43.53	0.444	
		147.2	59.47	0.404	
		196.2	72.06	0.367	T = 0.34N + 0.203
2.	08-10-87	19.6	6.94	0.354	
		39.2	14.37	0.367	
		58.9	19.33	0.328	
		78.5	26.77	0.341	
		98.1	34.20	0.349	
		147.2	49.07	0.333	
		196.2	65.18	0.332	
		58.9	21.81	0.360	
		245.3	85.01	0.347	T = 0.389N - 1.566
3.	08-10-87	19.6	5.70	0.291	
		39.2	11.90	0.304	
		58.9	19.33	0.328	
		78.5	28.01	0.357	
		98.1	37.92	0.387	
		147.2	55.27	0.375	
		196.2	73.86	0.376	
		39.2	18.09	0.461	
		245.3	94.93	0.387	T = 0.336N + 8.495

AVERAGE FRICTION COEFFICIENT = 0.355; STANDARD DEVIATION = 0.295


SURFACE - 4
TEST PANEL RESULTS
NORMAL FORCE (N)
TANGENTIAL FORCE (N)
250
225
200
175
150
125
100
75
50
25
0
0
10
20
30
40
50
60
70
80
90
100
1
2
3
1 T = 0.340N + 0.203
2 T = 0.389N - 1.566
3 T = 0.336N + 0.495
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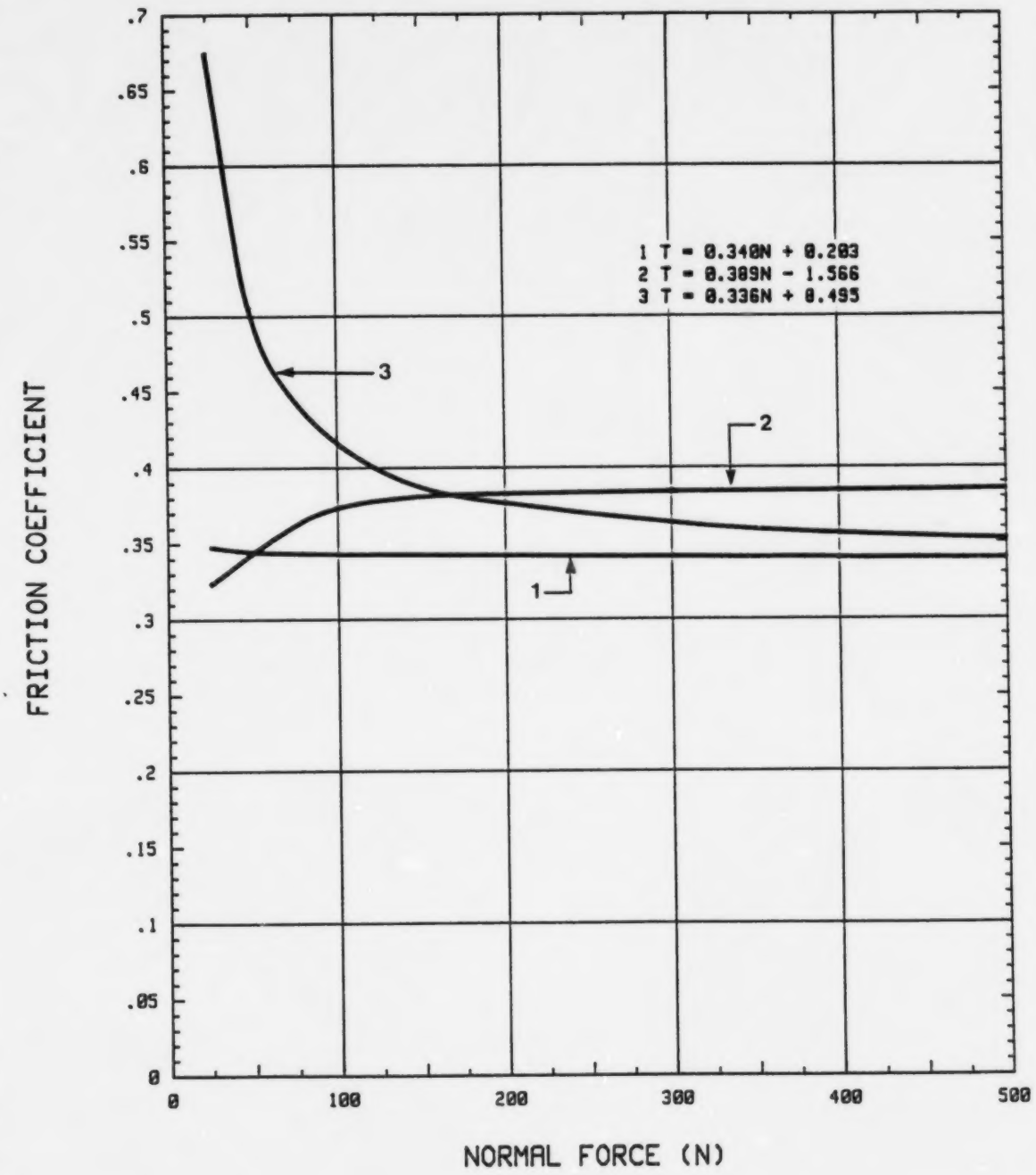
SURFACE - 4
FRICTION VERSUS NORMAL FORCE



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APPENDIX 3

IMD REPORT

National Research Council Canada
Institute for Marine Dynamics

Conseil national de recherches Canada
Institut de dynamique marine

THE EFFECT OF SURFACE FRICTION ON SHIP MODEL RESISTANCE IN LEVEL ICE

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THE EFFECT OF SURFACE FRICTION ON SHIP MODEL RESISTANCE IN LEVEL ICE

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SUMMARY This report describes a series of model tests and laboratory experiments carried out in the ice tank at IMD, between September 1986 and February 1987, for Melville Shipping Ltd., and sponsored by the Transportation Development Centre. The purpose of the tests was to study the effect of friction between the ship model and the ice on the resistance measurements in level ice. The model test results show the effect of surface finish, characterized by friction coefficient or surface roughness, on resistance, within the range of parameters covered.

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SYMBOLS

SYMBOL	QUANTITY	UNITS
CG	location of centre of gravity	
GM	height of metacentre above CG	m
g	acceleration due to gravity	m/sec^2
h	ice thickness	mm
K_{Ic}	fracture toughness	$kPa\text{-}m^{½}$
k	radius of gyration	m
n	shaft revolution rate	rps
P_D	power delivered	W
Q	torque	
R	resistance	N
R_c	resistance at reference ice condition	N
T	thrust	N
t	thrust deduction	
v	speed	m/sec
ΔR_p	increment of R with change in p	N
σ_f	flexural strength	kPa
σ_c	uniaxial compressive strength	kPa
τ	period of oscillation	sec
μ	coefficient of friction	

THE EFFECT OF SURFACE FRICTION ON SHIP MODEL RESISTANCE IN LEVEL ICE

1 INTRODUCTION

This report describes a series of model tests and laboratory experiments carried out in the ice tank at IMD, between September 1986 and February 1987, for Melville Shipping Ltd. and sponsored by the Transportation Development Centre. The purpose of the tests was to study the effect of friction between the ship model and the ice on resistance measurements in level ice.

The importance of friction on ship performance is considered in References 1 to 3. To study the effect of ice friction in model tests, the Ice Committee of the 17th ITTC organized a series of tests for the standard model, with a coefficient of friction for the model surface and the ice which would be higher than that used in the first series (Ref. 4). The results to date, along with the corresponding results for the full scale ship, are contained in the committee's report to the 18th ITTC (Ref. 5).

The consideration of friction effects has lead to study of the definition and measurement of ship–ice friction. Experiments by Forland and Tatinclaux with model ice (Ref. 6) have shown the influence of some ice parameters and test procedures on laboratory measurements of friction coefficient. Full scale measurements of friction forces have been made both with large samples (Ref. 7), and in–situ (Refs. 8,9). In the Polarstern experiments (Refs. 7,8), the ice, the painted surface, and the environmental conditions were similar, but the friction coefficients for the sample and in–situ measurements differed by a factor of 4 to 8. The results obtained to date show not only that the factors governing friction forces are complex, but also that the classification and definition of these forces are not yet complete.

If defining and measuring the friction coefficient for a given surface is difficult, the inverse problem, that of producing a surface with a given friction coefficient, is even less tractable. Development programs with this objective have been undertaken at major ice

tanks, including WARC (Ref. 10), and HSVA (Ref. 11). Experience has shown that processes which use extenders or matting agents in the paint to adjust friction coefficient are difficult to control precisely. For the present study, the method adopted was to produce a range of surface characteristics with different surface finishing techniques, to characterize the surfaces with friction measurements and roughness measurements, and then to correlate the characterizations with the results of resistance tests.

The influence of one parameter in ship–ice interactions may be examined through variations of that parameter in repeated tests in which all other parameters are held fixed. In ship model measurements, the influence of ice thickness, ice strength, or ship speed is routinely considered. The influence of bow shape may also be studied. Accordingly, the intent of the friction test series was to carry out repeated tests, and vary only the surface finish of the model. The objective was expanded to include different surfaces on different parts of the model.

Section 2 outlines the development of model surface finishing techniques at IMD. In Section 3, the method for measurement of friction coefficient of a surface is described. The model test program is described in Section 4. Results are presented in Section 5. Conclusions and indications for further work are discussed in Section 6.

2 MODEL SURFACE FINISHING

A variety of model surface finishing techniques were investigated. Consideration was given to repeatability, uniformity over the model surface, and cost. The cost estimates included materials, labour, and the procedures required for safe use of the materials. The surfaces were required to withstand ice tank testing conditions. Samples of candidate surfaces were characterized by roughness and friction coefficient measurements.

The investigation showed that most one pot standard model finishes, when diluted with sufficient additives to achieve the required surface friction, were not strong enough to withstand the model ice testing. Highly durable, two pot, automotive Polyurethane Enamel

was the next choice. Here standard pressure pot automotive spray equipment with an outside-air supplied hood was used with a high solids, fast drying, two pot polyurethane primer to provide a system that is almost as fast as standard one pot finishes. Subsequent tests and tank experience proved that Dupont's Imron retained enough strength to provide a durable finish in the medium friction surface range. The characteristics of the Imron finished surface may be varied by the addition of an acrylic flattening agent to remove gloss, magnesium silicate to absorb oil and remove gloss, and a combination of thinners, catalysts and spray technique to achieve the spray qualities, and thus the drying pattern which gives the surface roughness desired.

Three variations of the Imron surface were selected for the model test program. The description, for surface preparation purposes, of each of the three selected surfaces is given in Table 1. A bow, a midbody, and a plate were finished with each surface. The model stern was finished with a surface similar to surface 1.

Friction coefficient measurements were carried out on each plate, as described in the following section. In order to further characterize each surface, and also to provide a correlation among the different pieces finished with the same surface, surface roughness measurements were made of each model piece and plate. The measurements are roughness averages with a Surtronic 3, taken over a 13 mm traverse length, with a 2.5 mm cutoff. These measurements are summarized in Table 2.

3 FRICTION MEASUREMENTS

The objective of the friction tests was to measure the coefficient of friction between the surface of the model and the top surface of the model ice. The case of a sample of ice sliding over a long plate of model surface, where the ice piece continuously encounters new surface, was thought to be most representative of broken pieces of ice sliding along the bow and sides of the model. In order to measure the friction force in this type of interaction without measuring any effects of acceleration, the ice sample was held in place by a load cell, and the section of model surface was moved beneath it at a uniform

speed.

An apparatus was constructed at IMD to measure the friction force in the configuration described. Referred to as the "Friction Jig", it consists of a 35 × 140 cm tray that holds a sample of the model surface. The tray is mounted at one end on a Unislide and at the other end it is supported on four Teflon rollers. This allows the tray to be moved back and forth at a uniform speed. The slider is moved by a threaded rod, driven by an electric motor. The motor RPM can be held constant for a wide range of torques.

A sample of ice, bottom surface frozen to an aluminum sample holder, is placed on top of the model surface plate in the area where the tray is supported by the rollers. This allows a large normal load to be placed on the ice sample without any deflection of the tray. The ice sample holder is equipped with a counterweight which allows the weight of the ice sample and the sample holder to be counterbalanced. The friction force measured is the force required to maintain the position of the balanced sample holder as the model surface plate moves beneath it.

Friction tests for the M. V. Arctic project were conducted at a single speed, 10 cm/s. The water on the model surface plate was removed with a rubber wiper before each test, and therefore these were, by definition, "dry" friction tests. However since the ice sample contains entrapped tank water (brine), and the temperature was not below 0°C, the model plate surface was wetted in the zone of contact with the ice. A range of normal loads, 2, 5, 10, 15, and 20 kg was used on a 14 × 14 cm (0.02 m) sample of model ice, yielding nominal normal pressures of 1, 2.5, 5, 7.5 and 10 kPa. Measurements were made at the same time as model tests whenever possible in order to match the ice strength. The friction tests were all carried out in the ice tank room, where the temperature ranges from 0° to +5°C during testing.

For a given ice sample, the friction force F is related to the normal force N by

$$F = \mu N + S,$$

where μ is the friction coefficient and S is the static offset. An example of a set of measurements for one ice sample is shown in Figure 1. Measurements for a particular surface with samples from different ice sheets yielded similar values for μ, although S varied due to zero drift in the instrumentation and to ice sample differences. The values of μ averaged over all the tests conducted for each surface are given in Table 3.

4 MODEL TEST PROCEDURES

The ice tank tests were carried out with a 1:30 scale model of the M. V. Arctic, with the new bow installed in 1986. Principal dimensions of the model are given in Table 4. The model was constructed in three parts, divided at sections 2.29 m and 4.81 m forward of the aft perpendicular. Three identical bows and three identical parallel midbodies were made from molded fibreglass. The stern was made of wood. One bow and one parallel midbody were finished with each of the three selected surfaces. The stern was finished with surface 1. The model parts fitted together tightly and rigidly in every combination. The model was fitted with a bare hub, cone, duct, and rudder.

Every test was made, as closely as possible, in the same ice conditions. The target thickness, 50 mm, and the strength, 19 kPa, were chosen because they are within the range of the ship operation, and are reliable tank conditions. An additional test, for one model configuration, was made at 40 mm thickness and 17 kPa. The percentage concentrations of EG/AD/S for the test series were 0.39/0.027/0.0.

Resistance measurements were made at four speeds for each of the nine possible model configurations. The tests were carried out according to IMD's standard test procedures, described in Reference 13. The model was ballasted to the same conditions for every test. The towing point was at the centre of gravity. The GM, determined by inclining, was 0.053 m. The radii of gyration were calculated from the pitch and roll periods of the model in the water, 1.5 sec. and 2.6 sec. respectively, using the estimate (Ref.14)

$$T = 2\pi k\sqrt{(1+a)/g \times GM},$$

where k is the radius of gyration, a = 0.2 for roll and a = 0.9 for pitch.

Two video records were obtained for every run. One camera was located above the bow of the model, directed towards the cusps forming around the bow. The second sighted along the side of the model, to record ice movement along the midbody.

5 RESISTANCE RESULTS

An example of the time history of resistance, model motions, and carriage speed, sampled at 20 Hz, is given in Figure 2. Figure 3 shows the expansion of a constant speed portion of this same run, including the backup channel used for resistance. The motion measurements are vertical displacements to port, to starboard and forward of the CG, from which pitch, heave, and roll may be calculated. The motions show, among other things, any disturbances experienced by the model during the run. The average resistance, shown in Tables 5,6, and 7 is calculated from the time history over intervals in which the motions, resistance, and speed are steady. The corresponding thickness reported is the average of measurements every two metres along the track traversed in that interval. The flexural strength is the intersection of the curve of the strength versus time for that ice sheet with the abcissa of test time. A strength value of zero indicates the model towed through presawn ice. The ice properties for each ice sheet are summarized in Table 8.

To comply with the requirement to compare results, the resistance data in Tables 5–7 are projected, where necessary, to the reference ice conditions of h = 50 mm and σ_f = 19 kPa. The adjustment for thickness, ΔR_h, is based on the comparison of the resistances at 40 mm and 50 mm, shown in Figure 4, and is taken as 0.3%/mm. The adjustment for strength, ΔR_σ, is calculated by assuming a linear dependence on σ_f between the presawn ice and the

target, or obtained, σ_f. While these adjustments are approximate, they are consistent with the relationships obtained in previous model tests (Ref. 15). The resistance at reference ice conditions,

$$R_c = R + \Delta R_h + \Delta R_\sigma,$$

is also contained in Tables 5-7.

Figures 5 to 10 are plotted for the reference ice conditions. The level ice resistance is RTOTAL, and the resistance measured in presawn ice is RSUBMERGE.

The effect of bow surface finish on resistance is shown in Figures 5 to 7, resistance versus speed for one midbody and each of the three bows. Similarly, the effect of midbody surface finish on resistance is shown in Figures 8 to 10, resistance versus speed for one bow and each of the three midbodies. The corresponding results for presawn ice are shown on the same figures.

6 DISCUSSION

The three model surfaces tested were characterized by roughness and friction coefficient. Considering the data in Tables 2 and 3, surface 2 has clearly the lowest friction coefficient and the lowest roughness. Surface 3 has a slightly higher friction coefficient than surface 1, although the difference is within the range of experimental error. For the plates on which the friction was measured, the roughness of surface 1 is 14% higher than the roughness of surface 3. The roughness of the surface 1 and surface 3 midbodies is almost the same. For the bows, however, the roughness of surface 3 is higher than the roughness of surface 1, by 8%.

In Figures 5 to 7, it may be seen that for every midbody, bow 2 has the lowest resistance, and that this effect is strongest with midbody 2. The resistances of bows 1 and 3 are close, but bow 1 is consistently higher. The pattern holds true for submergence resistance as well.

The data in Figures 8 to 10 are grouped according to bow, to show the effect of changing midbodies. With the smooth bow, the resistances are lowest for midbody 2, and slightly higher for midbody 1. For bows 1 and 3, the differences in resistance due to midbody surface are not well distinguished. Once again, the trend continues for the submergence resistance.

Relative resistances for all the surface configurations, for one particular speed, may be seen in Figure 11. Resistance is presented as a percentage of the resistance for the model with bow 2 and midbody 2, at 0.5 m/s. The resistances for one midbody may be seen in one bar; the resistances for one bow have a common pattern.

In all the results, the character of surface 2 is clear: low roughness, low friction, low resistance. Increasing the friction of either the bow or the midbody increases the resistance, but the effect is not additive; increasing the midbody friction with a high friction bow adds less resistance than increasing the midbody friction with a smooth bow. The reason for this is not known, but study of the motion of the ice pieces on the videos may provide some clues.

Surfaces 1 and 3 may be grouped together as having differences which are not reliable within the context of possible experimental error. However within the range of these two surfaces, a consistent pattern appears in the correlation between lower roughness and higher forces. On the plates, the higher forces are seen in higher friction coefficients; on the models the forces are resistances. Considering ice deformation properties, this pattern is feasible within a narrow band of roughness, but would not be expected to persist to much lower, or higher, roughness.

The model test results show the effect of surface finish, characterized by friction coefficient or surface roughness, on resistance, within the range of parameters covered. The effect at higher or lower speeds, the effect of a surface with a significantly higher friction coefficient, or the results for different ship forms are topics which still require investigation.

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MODEL SURFACE FINISH

PAINT INGREDIENTS AND METHODS

	Surface 1	Surface 2	Surface 3
Imron A	2 quarts	2 quarts	2 quarts
Imron B	½ quart	½ quart	½ quart
magnesium silicate	—	400 gm	400 gm
catylist	14 gm	14 gm	14 gm
thinner	200 gm	200 gm	200 gm
air	50 spi	50 psi	60 psi
flattening agent	—	300 gm	300 gm
note	—	—	reduced fluid flow

M. V. ARCTIC
FRICTION COEFFICIENTS

Surface 1	0.060 ± 0.007
Surface 2	0.004 ± 0.001
Surface 3	0.062 ± 0.009
Stern	0.099 ± 0.009

M. V. ARCTIC

ROUGHNESS AVERAGES

μm ± standard deviation

	Surface 1	Surface 2	Surface 3
Bow	1.291 ± 0.189	0.490 ± 0.302	1.389 ± 0.268
Midbody	1.276 ± 0.340	0.276 ± 0.085	1.269 ± 0.236
Plate	1.206 ± 0.191	0.483 ± 0.162	1.052 ± 0.149
Stern	1.304 ± 0.193	.—	.—
Stern plate	1.290 ± 0.207	.—	.—

M. V. ARCTIC

MODEL DESCRIPTION AND TEST CONDITION

scale	1:30	
length between perpendiculars	6.872	m
waterline beam at midships	0.762	m
draft at midships	0.366	m
draft at aft perpendicular	0.366	m
draft at fwd perpendicular	0.366	m
volume of displacement	1.395	m^3
displacement	1393.4	kg
CG fwd of midships	-0.014	m
CG above keel	0.283	m
transverse GM	0.053	m
longitudinal GM	10.265	m
radius of gyration in roll	0.267	m
radius of gyration in pitch	1.718	m

M. V. ARCTIC

LEVEL ICE RESISTANCE

TEST#	bow	mid	h	σ_f	v	R	ΔR_σ	ΔR_h	R_c
2	1	1	49	19	0.19	76	0.0	+2.0	78
2	1	1	51	19	0.33	89	0.0	-2.0	87
2	1	1	49	19	0.47	103	0.0	+3.0	106
2	1	1	49	19	0.61	111	0.0	+3.0	114
3	1	1	39	17	0.19	50	+3.5	3.%	—
3	1	1	41	17	0.32	63	+3.0	3.%	—
3	1	1	40	17	0.46	70	+3.4	3.%	—
3	1	1	40	17	0.60	81	+4.5	3.%	—
3	1	1	39	0	0.19	20.5	—	—	—
3	1	1	41	0	0.32	37	—	—	—
3	1	1	40	0	0.46	41	—	—	—
3	1	1	40	0	0.60	43	—	—	—
4	2	1	49	19	0.18	46	0.0	+1.0	47
4	2	1	50	19	0.32	59	0.0	0.0	59
4	2	1	50	19	0.46	76	0.0	0.0	76
4	2	1	50	19	0.60	88	0.0	0.0	88
4	2	1	50	0	0.19	20	—	—	—
4	2	1	50	0	0.32	24	—	—	—
4	2	1	50	0	0.60	36	—	—	—
5	3	1	48	16	0.19	56	5.8	+3.5	65
5	3	1	49	16	0.33	74	7.5	+2.3	84
5	3	1	49	16	0.47	86	7.9	+2.6	97
5	3	1	49	16	0.60	103	9.3	+3.1	115
5	3	1	49	0	0.33	34	—	—	—
5	3	1	49	0	0.60	53	—	—	—
6	2	2	48	19	0.19	39	0.0	+2.0	41
6	2	2	48	19	0.33	45	0.0	+3.0	48
6	2	2	48	19	0.47	57	0.0	+3.0	60
6	2	2	48	19	0.60	60	0.0	+3.0	63
6	2	2	48	0	0.19	15	—	—	—
6	2	2	48	0	0.33	21	—	—	—
6	2	2	48	0	0.47	25	—	—	—
6	2	2	48	0	0.60	31	—	—	—

LEVEL ICE RESISTANCE
(continued)

TEST#	bow	mid	h	σ_f	v	R	ΔR_σ	ΔR_h	R_c
7	3	2	48	17	0.19	66	4.3	+2.2	73
7	3	2	50	17	0.33	78	4.8	+3.5	85
7	3	2	49	17	0.47	92	5.4	+2.8	100
7	3	2	50	17	0.60	101	5.4	+2.8	109
7	3	2	48	0	0.19	29	—	—	—
7	3	2	50	0	0.33	37	—	—	—
7	3	2	49	0	0.47	46	—	—	—
7	3	2	50	0	0.60	55	—	—	—
8	1	2	48	19	0.19	74	0.0	+4.0	78
8	1	2	50	19	0.33	93	0.0	+0.0	93
8	1	2	48	19	0.47	98	0.0	+5.0	103
8	1	2	50	19	0.60	119	0.0	+0.0	119
8	1	2	48	0	0.19	28	—	—	—
8	1	2	50	0	0.33	42	—	—	—
8	1	2	48	0	0.47	48	—	—	—
8	1	2	50	0	0.60	58	—	—	—
9	3	3	48	23	0.19	65	-6.8	+3.2	61
9	3	3	50	23	0.33	86	-8.3	0.0	78
9	3	3	49	23	0.47	97	-9.0	+2.4	90
9	3	3	50	23	0.60	124	-12.7	0.0	111
9	3	3	48	0	0.19	26	—	—	—
9	3	3	50	0	0.33	38	—	—	—
9	3	3	49	0	0.47	45	—	—	—
9	3	3	50	0	0.60	51	—	—	—
10	2	3	51	18	0.19	51	+1.6	-1.5	51
10	2	3	54	18	0.33	65	+1.9	-7.5	59
10	2	3	52	18	0.47	78	+2.1	-4.5	76
10	2	3	53	18	0.60	89	+2.6	-7.7	84
10	2	3	51	0	0.19	23	—	—	—
10	2	3	54	0	0.33	31	—	—	—
10	2	3	52	0	0.47	40	—	—	—
10	2	3	53	0	0.60	43	—	—	—

LEVEL ICE RESISTANCE (continued)

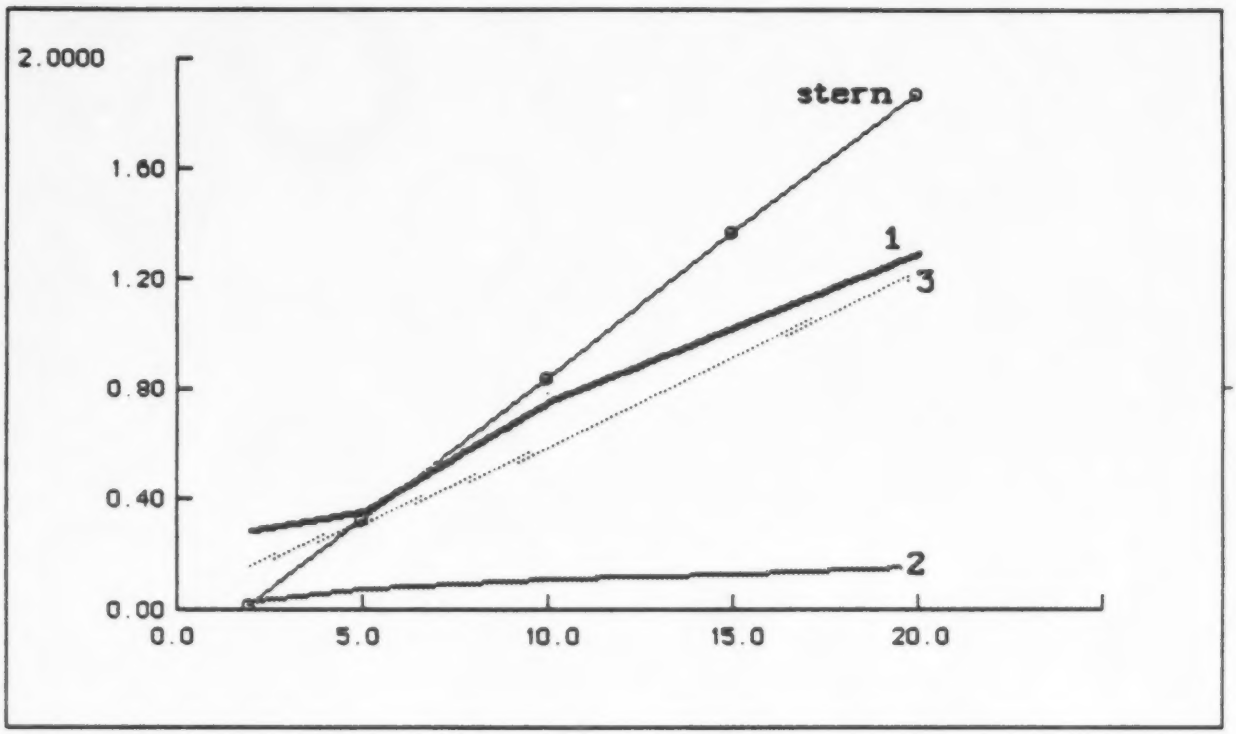
TEST*	bow	mid	h	σ_f	v	R	ΔR_σ	ΔR_h	R_c
11	1	3	46	21	0.19	77	-4.7	+8.1	80
11	1	3	48	21	0.33	84	-3.3	+4.5	85
11	1	3	47	21	0.60	109	-3.0	+8.9	115
11	1	3	46	0	0.19	28	—	—	—
11	1	3	48	0	0.33	49	—	—	—
11	1	3	47	0	0.60	78	—	—	—

FRICTION SERIES

ICE PROPERTIES

TEST*	h	σ_f	σ_f/K_{Ic}	E/σ_f	σ_c	p
2	50	19	6	1100	42	0.9428
3	40	17	~	1185	36	0.9479
4	50	19	~	1510	~	0.9438
5	48	19	4	1970	49	0.9432
6	48	19	9	2100	41	0.9423
7	49	17	7	1900	48	0.9428
8	49	19	7	1575	46	0.9419
9	49	23	6	2270	60	0.9413
10	53	18	6	1675	57	0.9410
11	47	21	8	1072	59	0.9421

Figure 1



Friction Force vs Normal Force

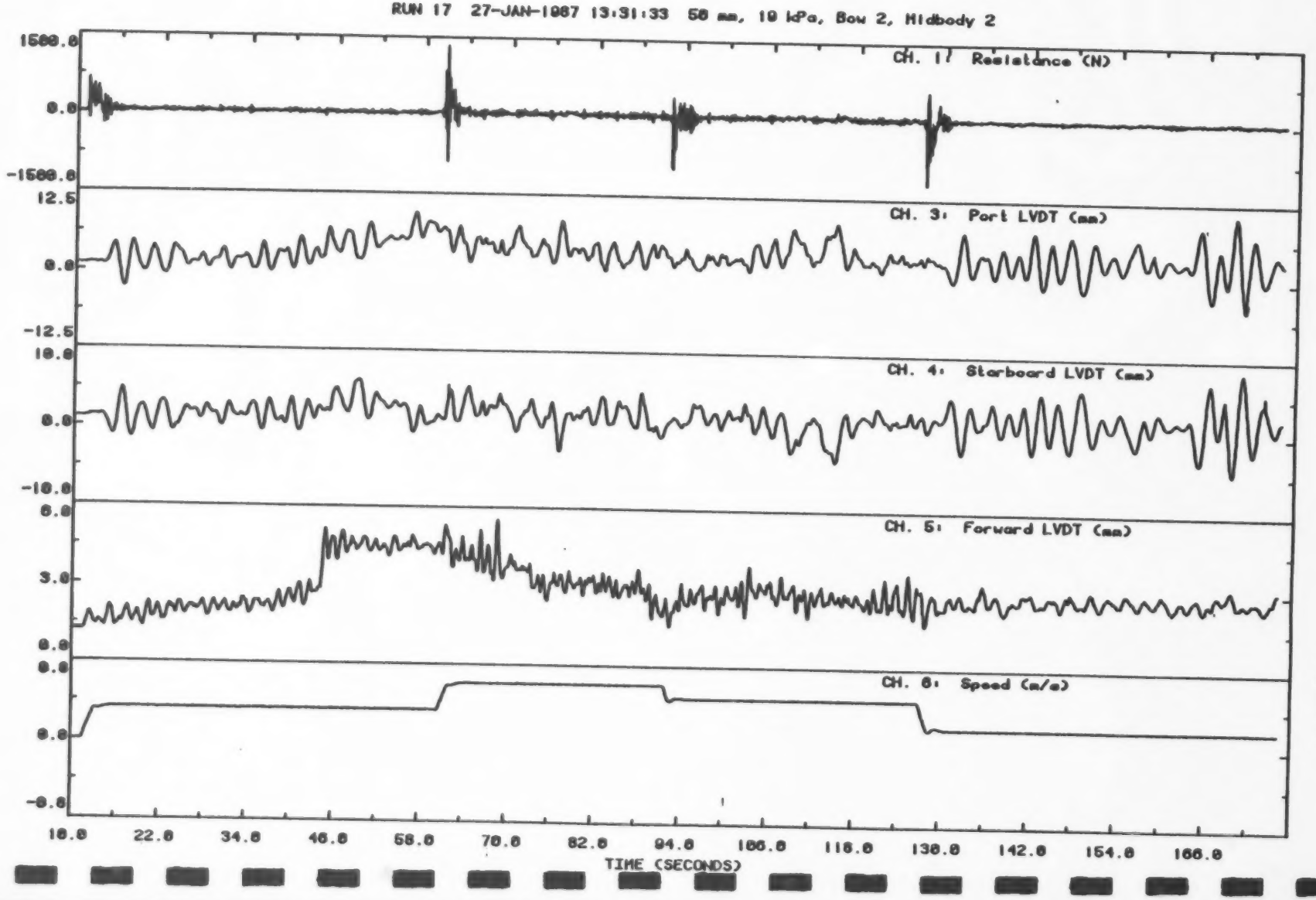

RUN 17 27-JAN-1987 13:31:33 50 mm, 19 kPa, Bow 2, Midbody 2
1500.0
0.0
-1500.0
CH. 1: Resistance (N)
12.5
0.0
-12.5
CH. 3: Port LVDT (mm)
10.0
0.0
-10.0
CH. 4: Starboard LVDT (mm)
6.0
3.0
0.0
CH. 5: Forward LVDT (mm)
0.0
0.0
-0.0
CH. 6: Speed (m/s)
10.0
22.0
34.0
46.0
58.0
70.0
82.0
94.0
106.0
118.0
130.0
142.0
154.0
166.0
TIME (SECONDS)

Figure 2

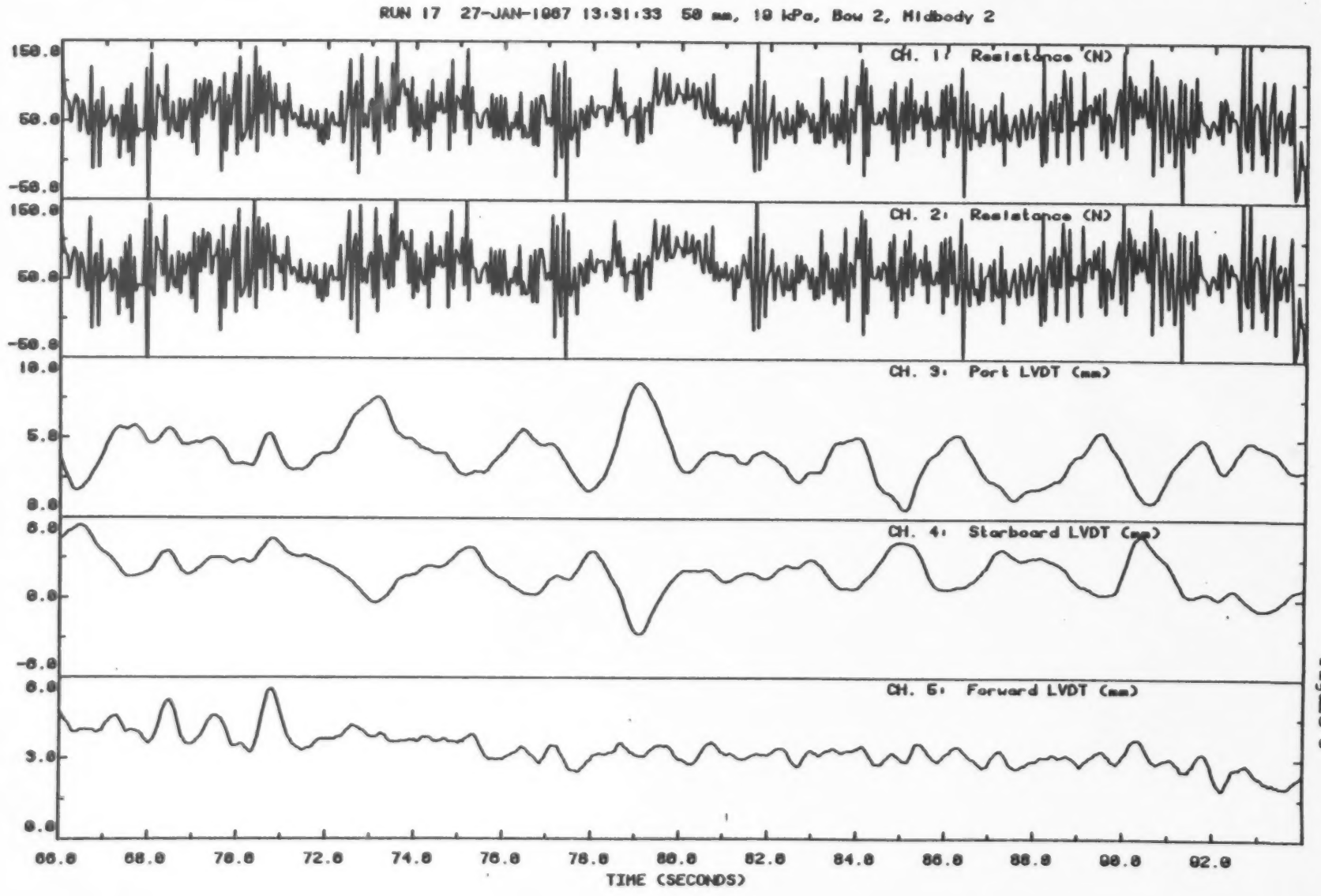

RUN 17 27-JAN-1987 13:31:33 50 mm, 10 kPa, Bow 2, Midbody 2
CH. 1: Resistance (N)
150.0
50.0
-50.0
CH. 2: Resistance (N)
150.0
50.0
-50.0
CH. 3: Port LVDT (mm)
10.0
5.0
0.0
CH. 4: Starboard LVDT (mm)
6.0
0.0
-6.0
CH. 5: Forward LVDT (mm)
6.0
3.0
0.0
66.0 68.0 70.0 72.0 74.0 76.0 78.0 80.0 82.0 84.0 86.0 88.0 90.0 92.0
TIME (SECONDS)

Figure 3

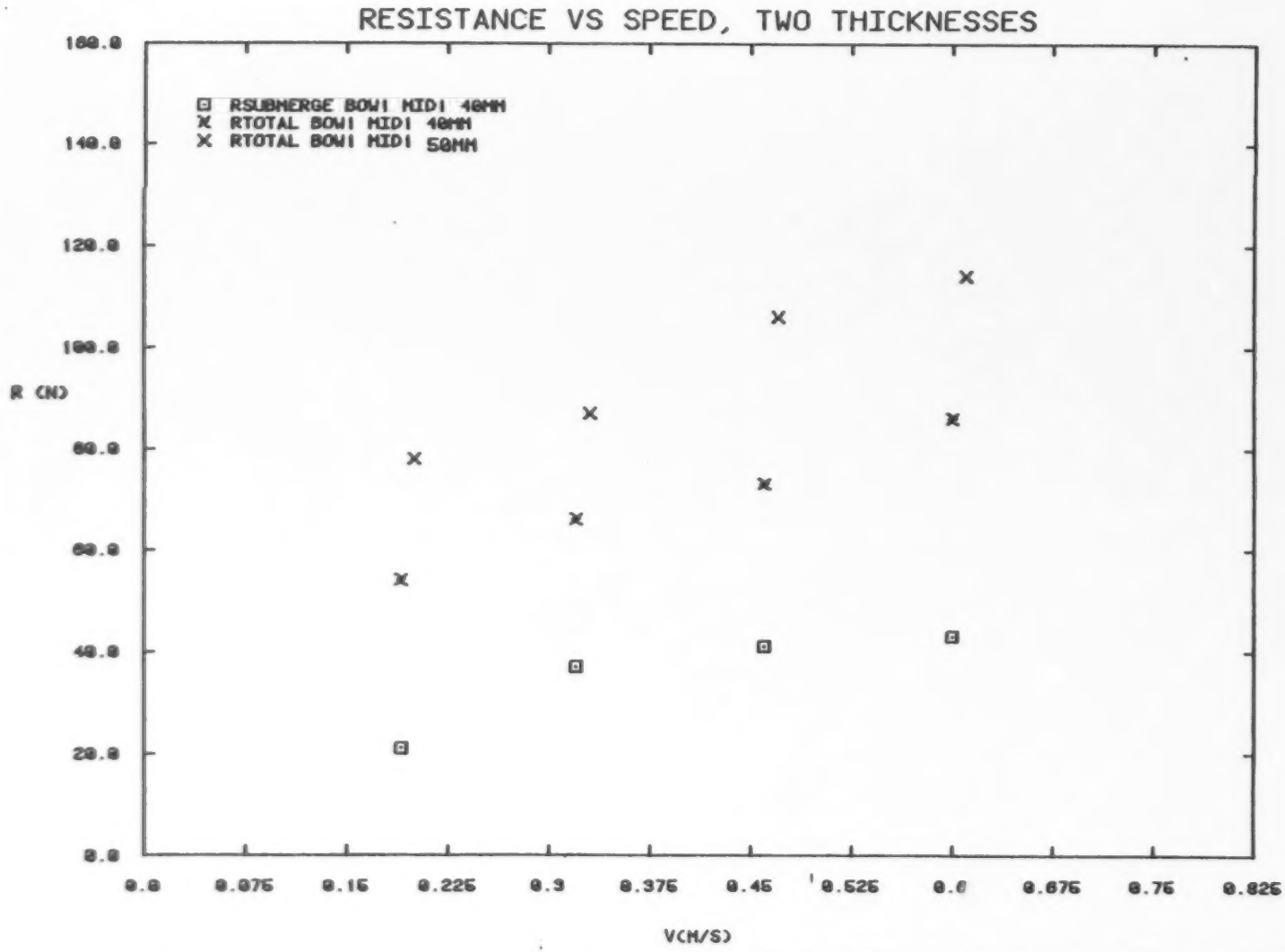
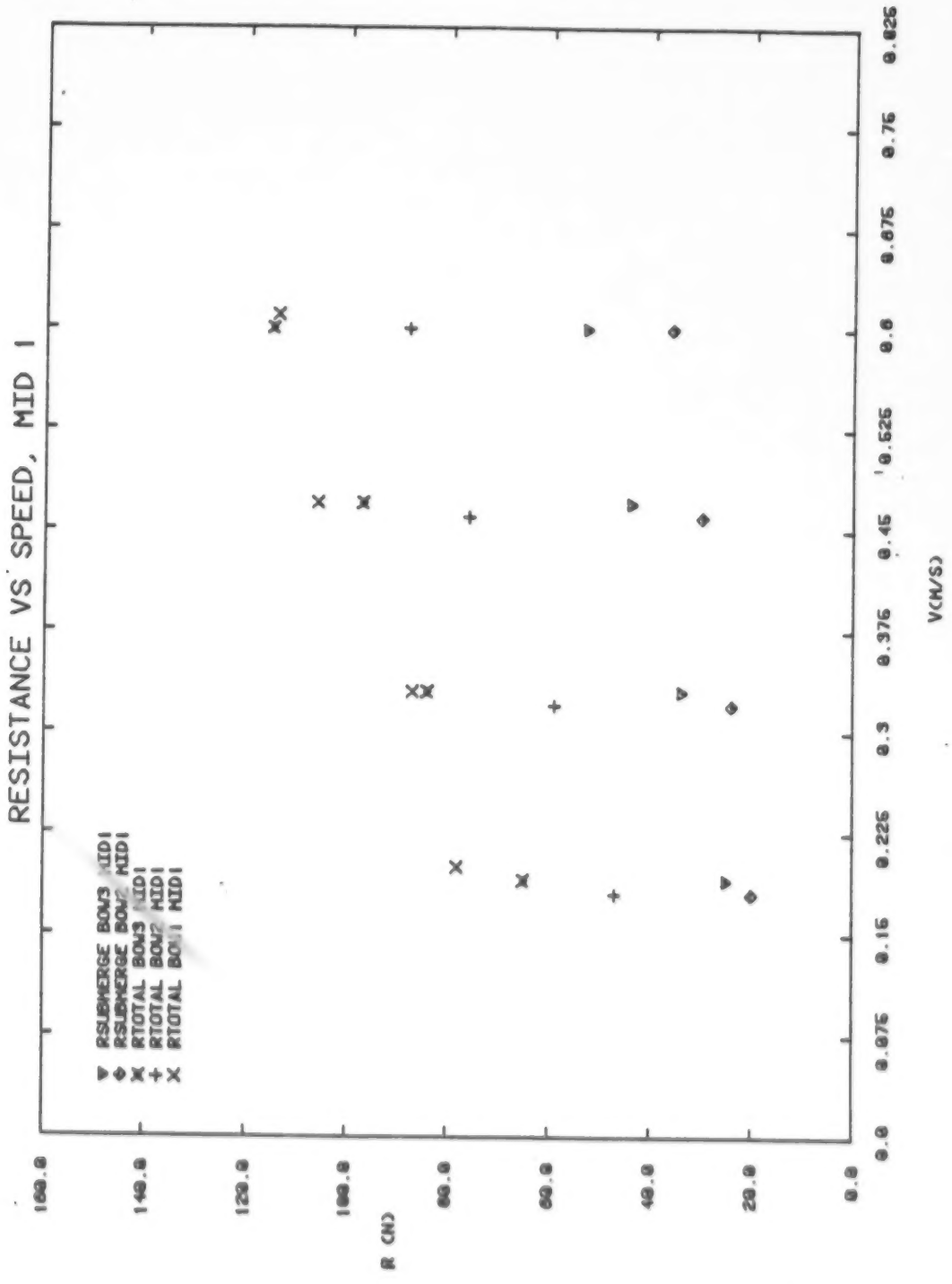

RESISTANCE VS SPEED, TWO THICKNESSES
RSUBMERGE BOWI MIDI 40MM
RTOTAL BOWI MIDI 40MM
RTOTAL BOWI MIDI 50MM
R (N)
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
0.0
0.075
0.15
0.225
0.3
0.375
0.45
0.525
0.6
0.675
0.75
0.825
V(M/S)

Figure 4

Figure 5


RESISTANCE VS SPEED, MID 1
RSUBMERGE BOW3 MID1
RSUBMERGE BOW2 MID1
RTOTAL BOW3 MID1
RTOTAL BOW2 MID1
RTOTAL BOW1 MID1
R (N)
V(M/S)
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
0.075
0.15
0.225
0.3
0.375
0.45
0.525
0.6
0.675
0.75
0.825

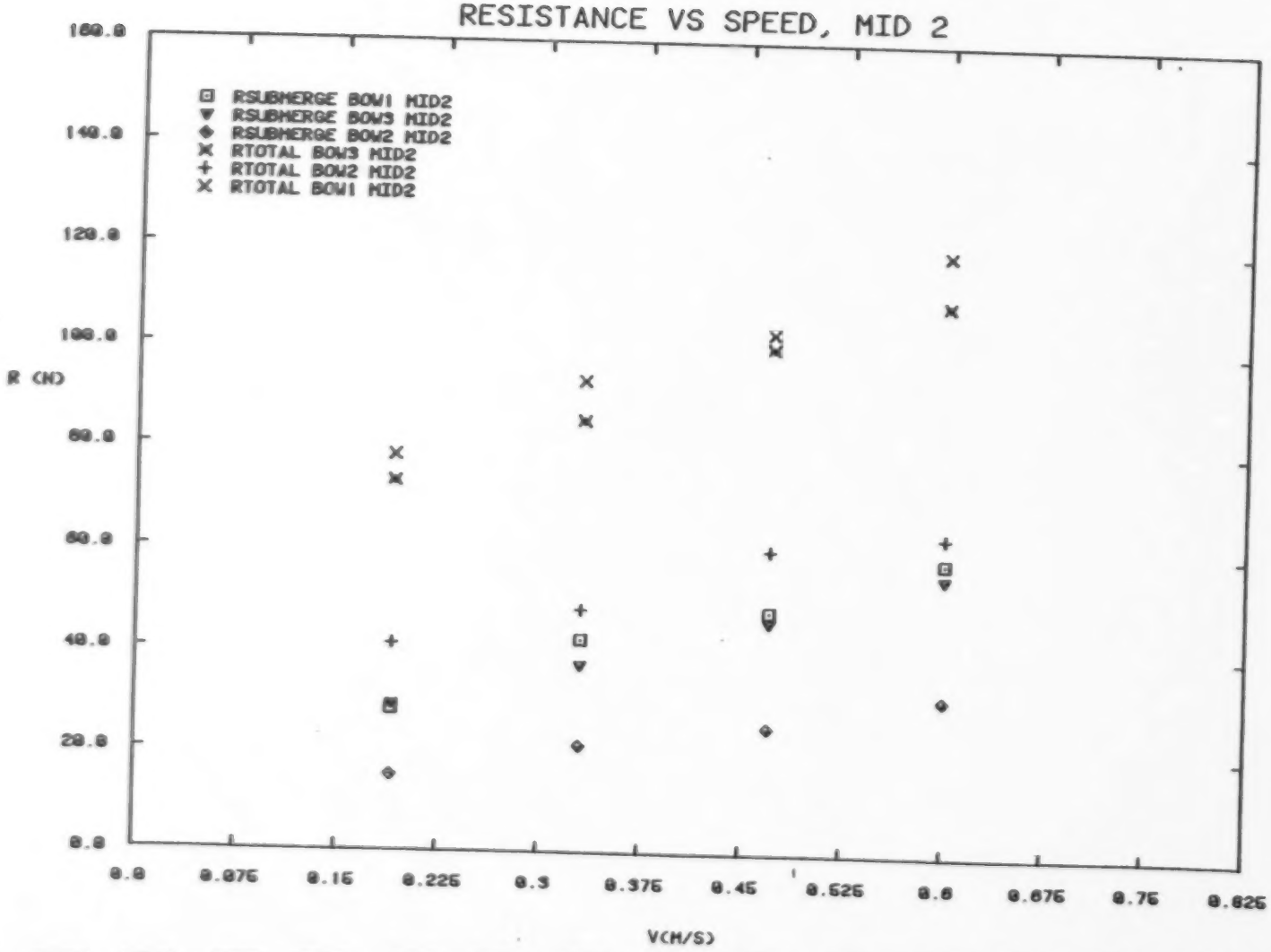

RESISTANCE VS SPEED, MID 2
RSUBMERGE BOW1 MID2
RSUBMERGE BOW3 MID2
RSUBMERGE BOW2 MID2
RTOTAL BOW3 MID2
RTOTAL BOW2 MID2
RTOTAL BOW1 MID2
R (N)
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
0.0
0.075
0.15
0.225
0.3
0.375
0.45
0.525
0.6
0.675
0.75
0.825
V(M/S)

Figure 6

Figure 7

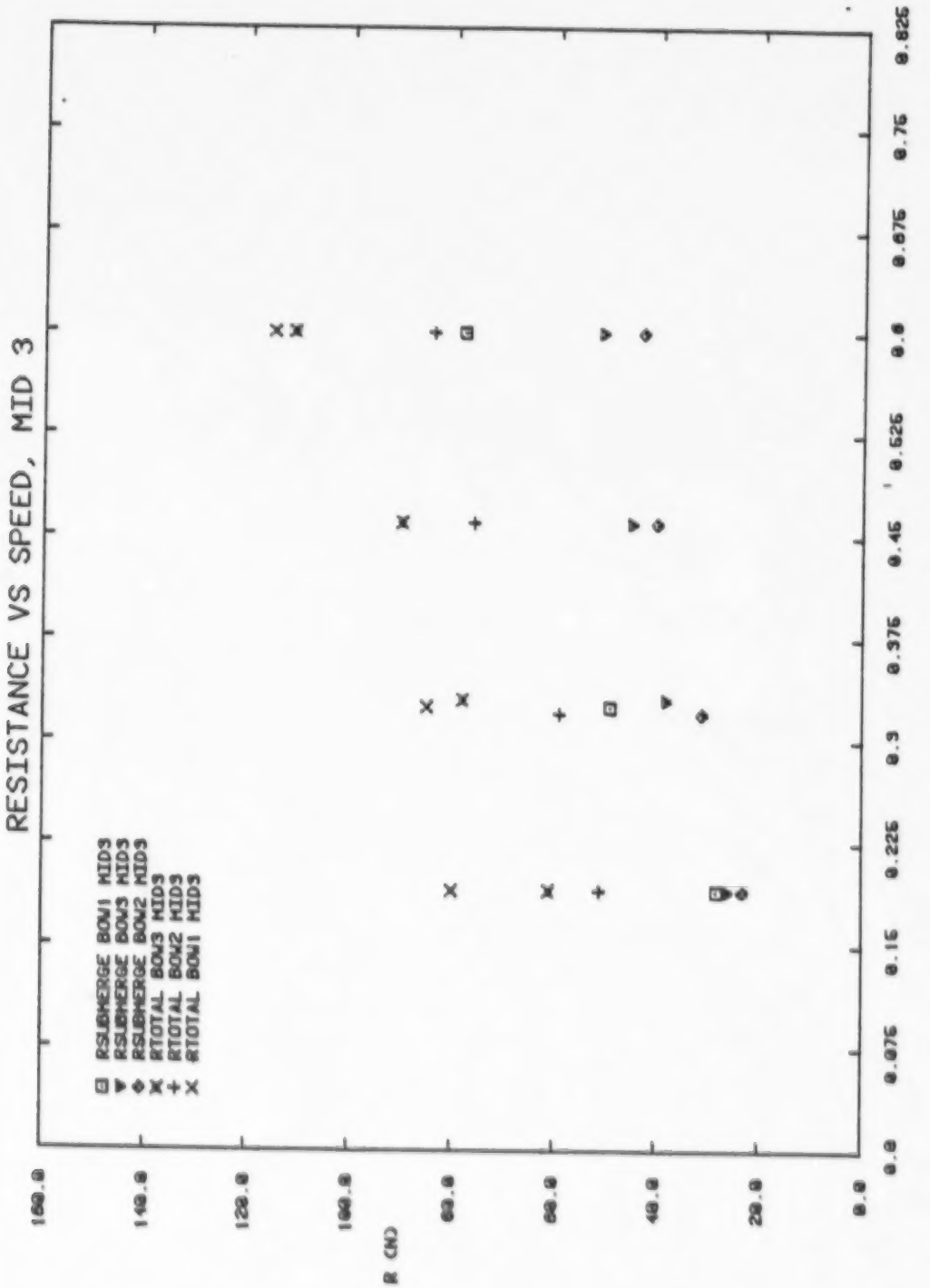
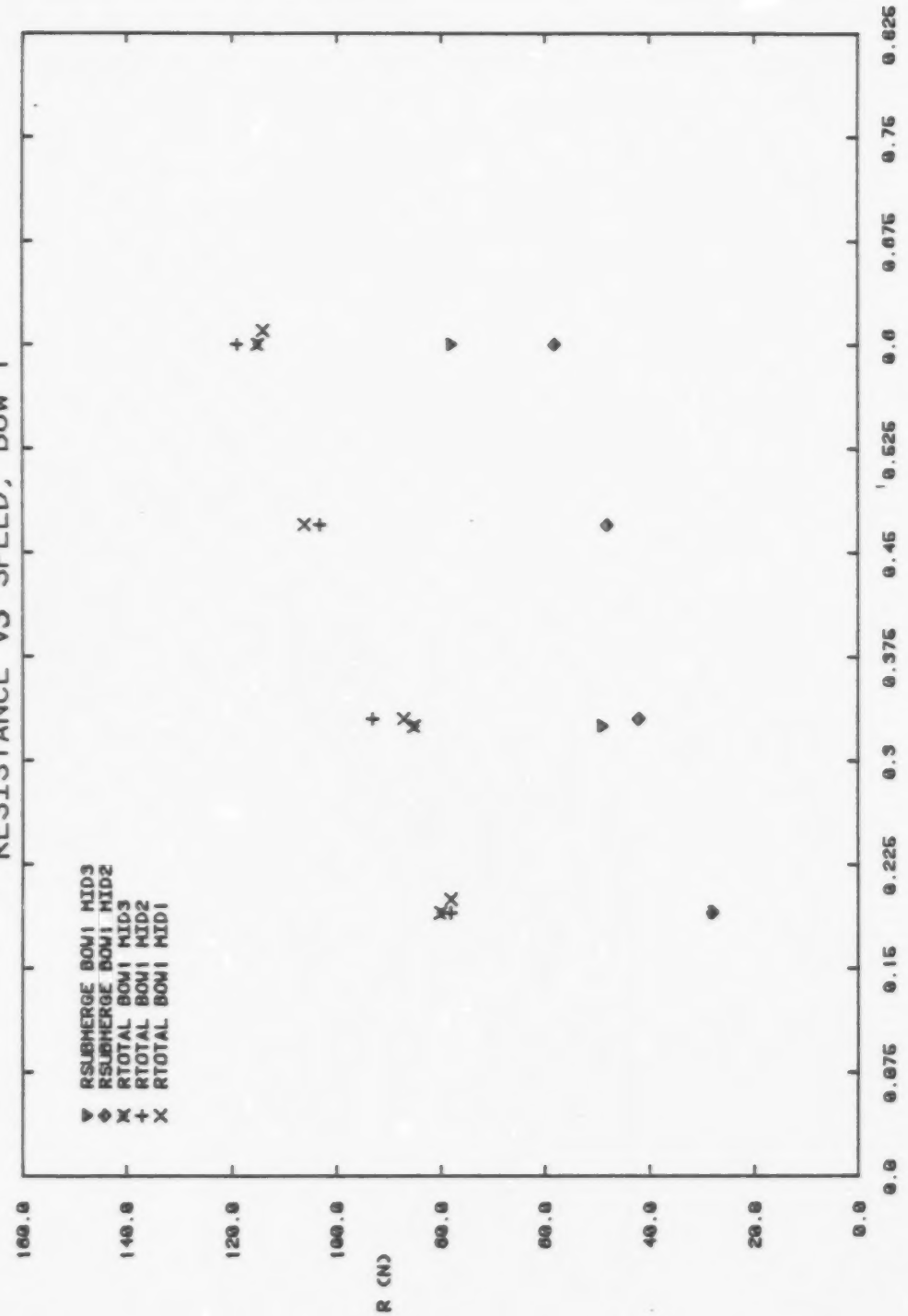

RESISTANCE VS SPEED, MID 3
RSUBMERGE BOW1 MID3
RSUBMERGE BOW3 MID3
RSUBMERGE BOW2 MID3
RTOTAL BOW3 MID3
RTOTAL BOW2 MID3
RTOTAL BOW1 MID3
R (N)
V(M/S)
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
0.0
0.075
0.15
0.225
0.3
0.375
0.45
0.525
0.6
0.675
0.75
0.825

Figure 8


RESISTANCE VS SPEED, BOW 1
RSUBMERGE BOW1 MID3
RSUBMERGE BOW1 MID2
RTOTAL BOW1 MID3
RTOTAL BOW1 MID2
RTOTAL BOW1 MID1
R (N)
V(M/S)
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
0.0
0.075
0.15
0.225
0.3
0.375
0.45
0.525
0.6
0.675
0.75
0.825

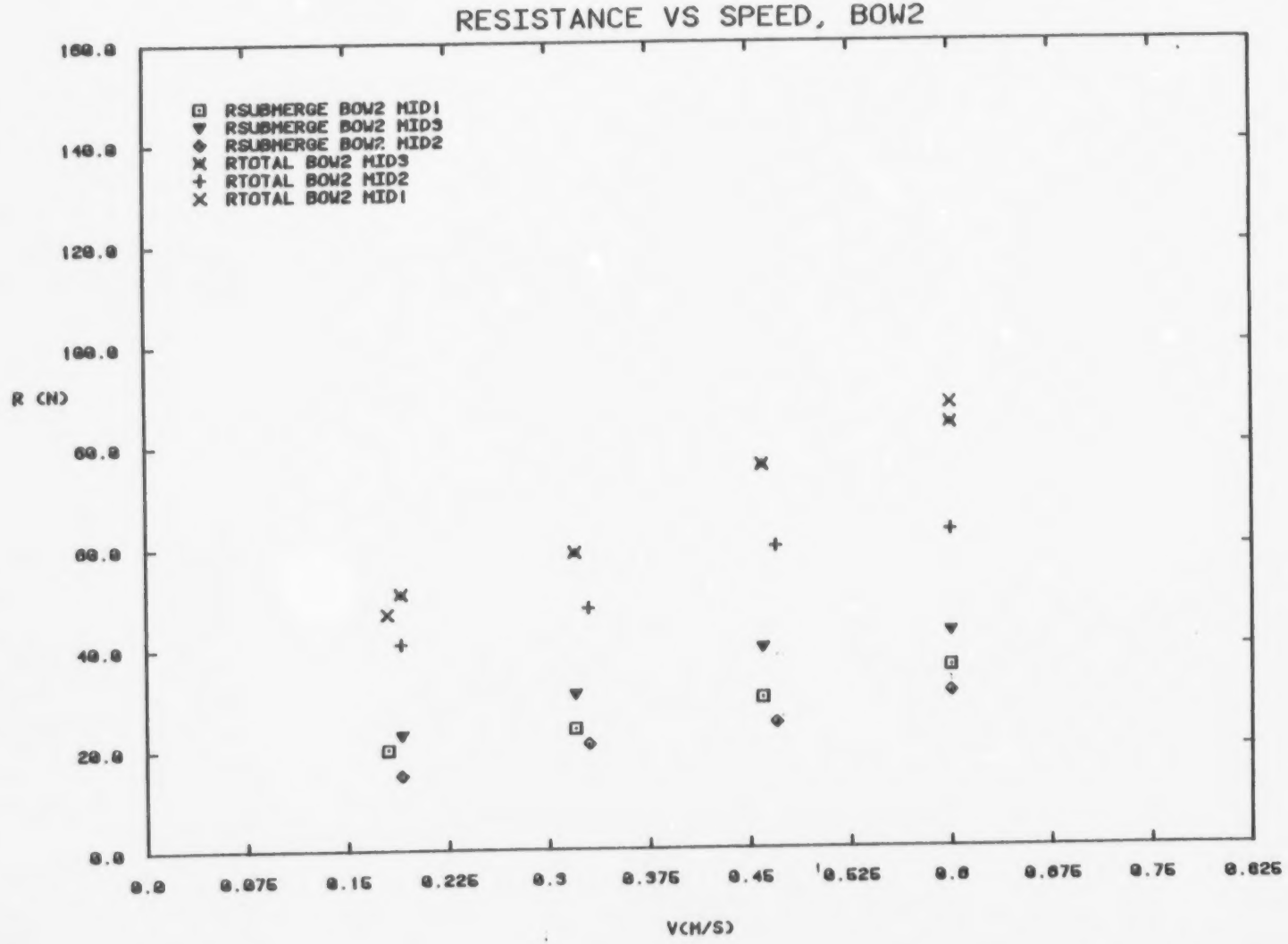

RESISTANCE VS SPEED, BOW2
RSUBMERGE BOW2 MID1
RSUBMERGE BOW2 MID3
RSUBMERGE BOW2 MID2
RTOTAL BOW2 MID3
RTOTAL BOW2 MID2
RTOTAL BOW2 MID1
R (N)
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
0.0
0.075
0.15
0.225
0.3
0.375
0.45
0.525
0.6
0.675
0.75
0.825
V(M/S)

Figure 9

Figure 10

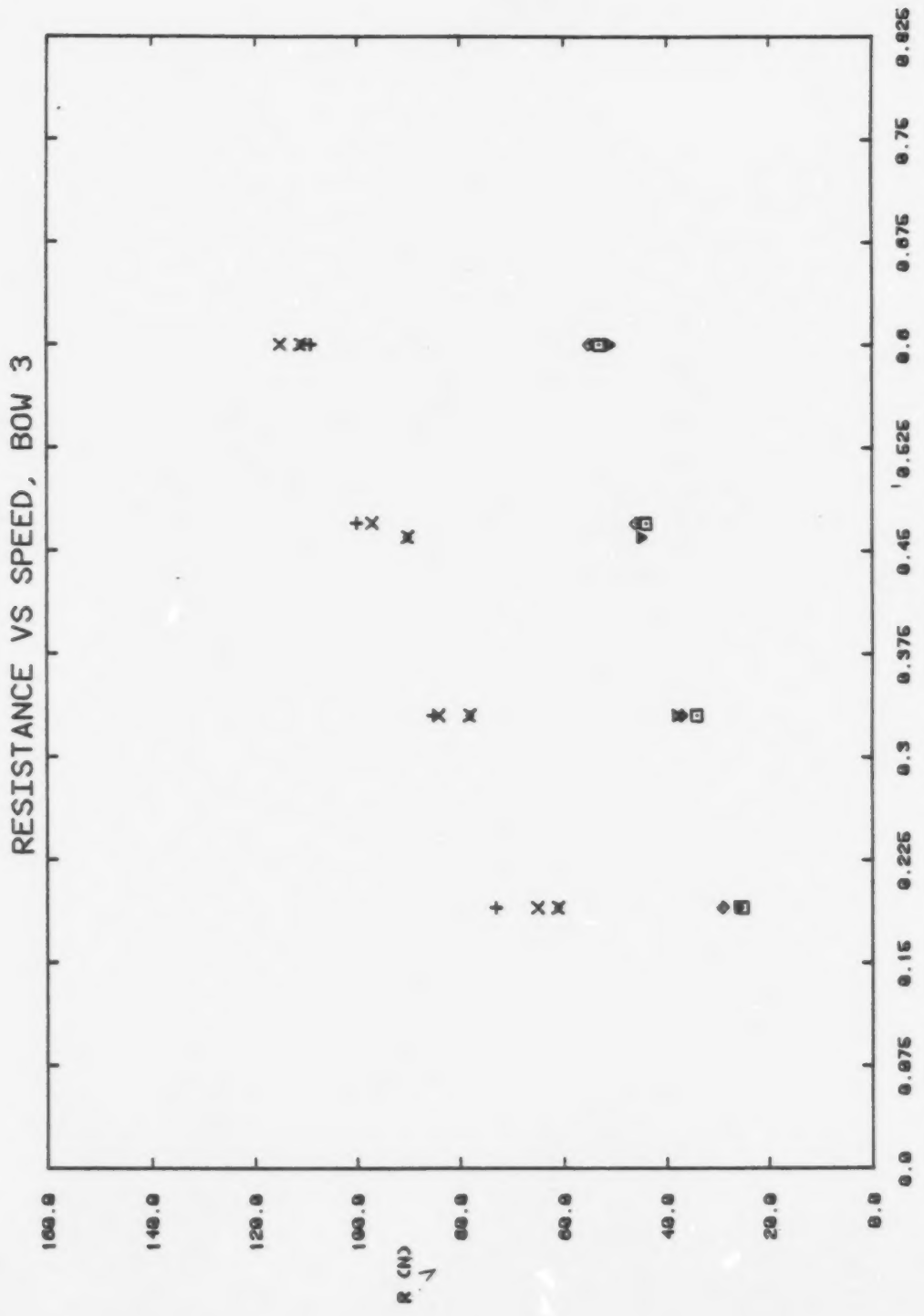
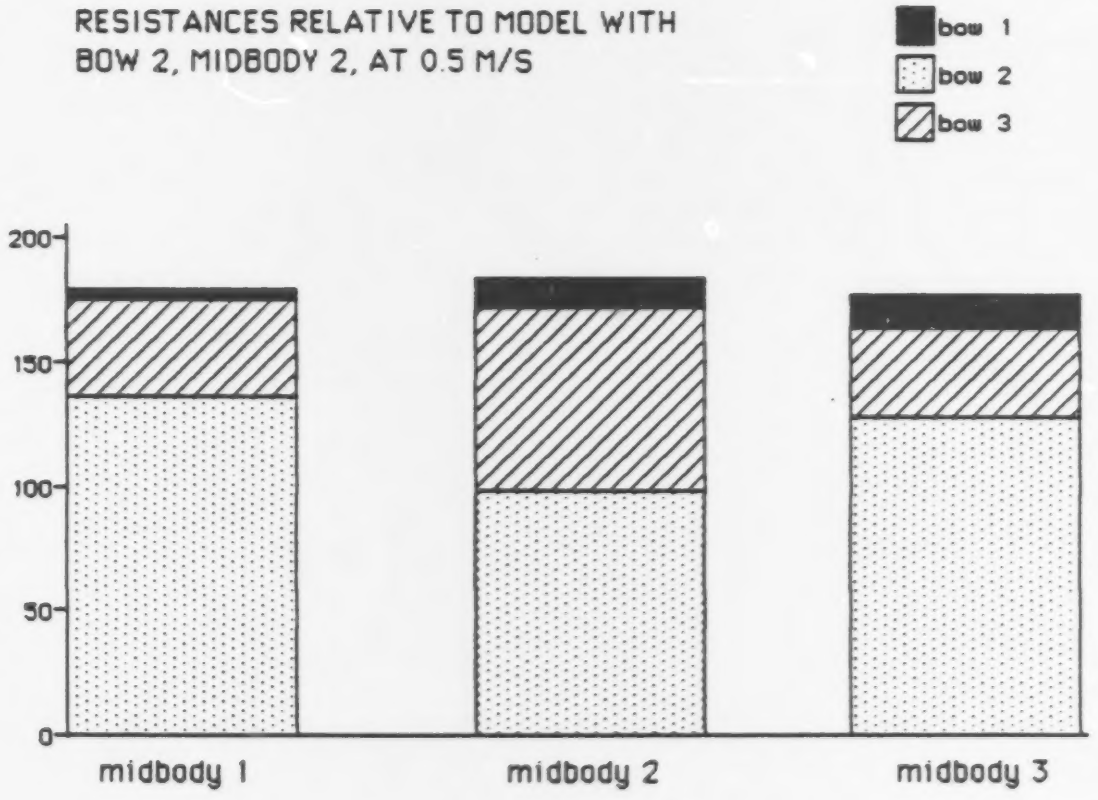

RESISTANCE VS SPEED, BOW 3
R (N)
V(M/S)
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
0.075
0.15
0.225
0.3
0.375
0.45
0.525
0.6
0.675
0.75
0.825

Figure 11

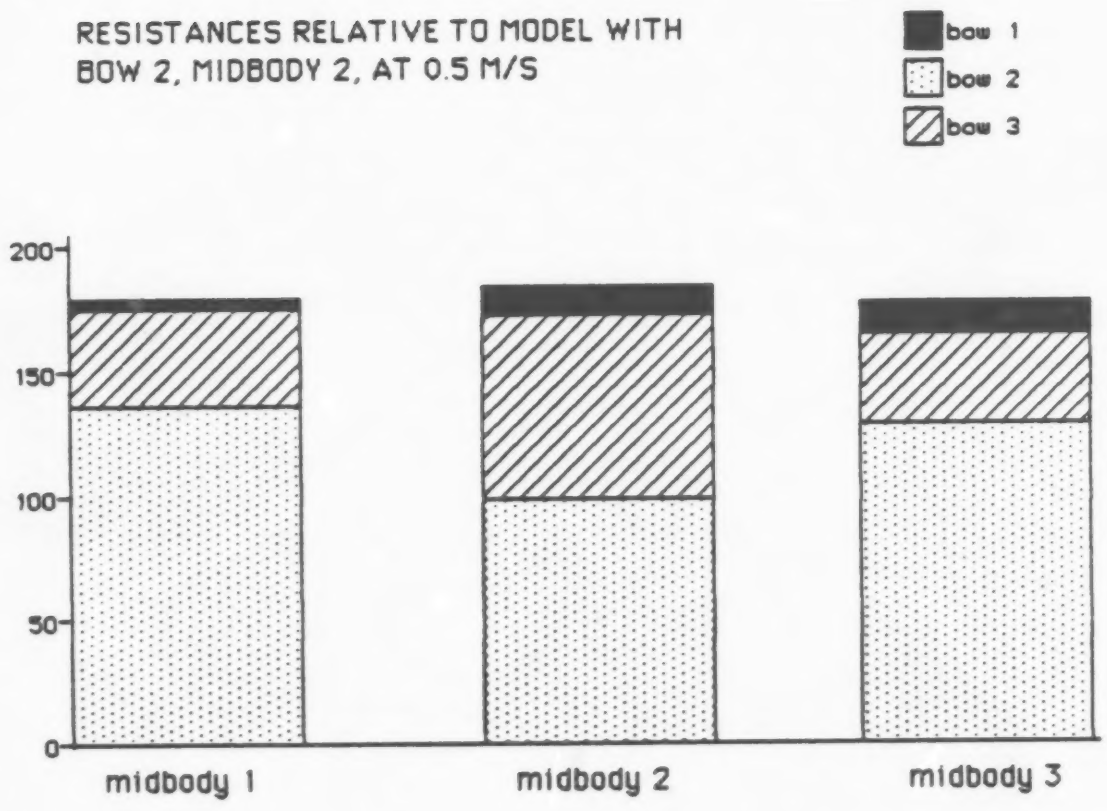
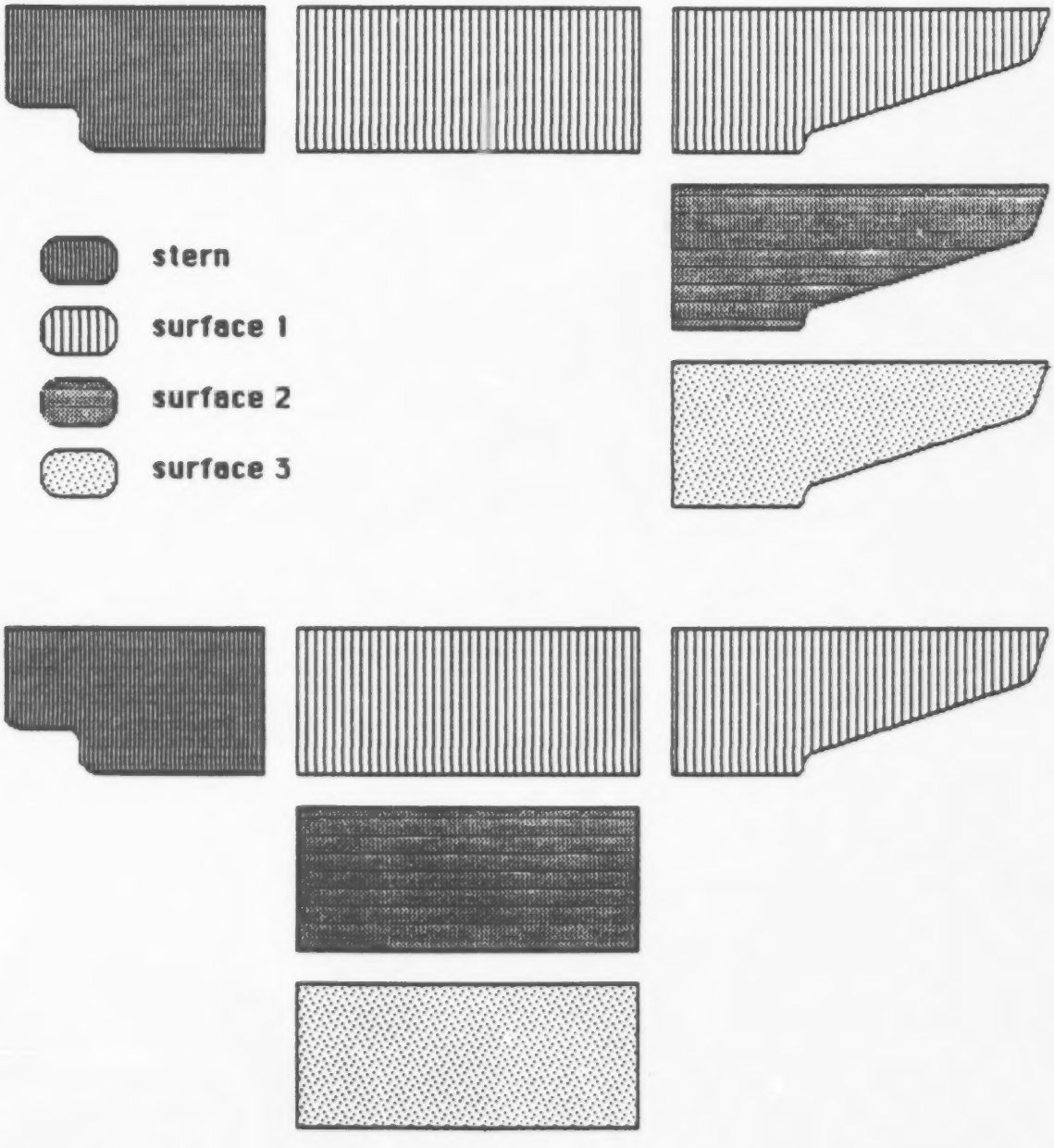
EFFECT OF BOW SURFACE ON RESISTANCE

RESISTANCES RELATIVE TO MODEL WITH
BOW 2, MIDBODY 2, AT 0.5 M/S



EFFECT OF BOW SURFACE ON RESISTANCE

RESISTANCES RELATIVE TO MODEL WITH
BOW 2, MIDBODY 2, AT 0.5 M/S



M. V. ARCTIC MODEL
SURFACES TESTED